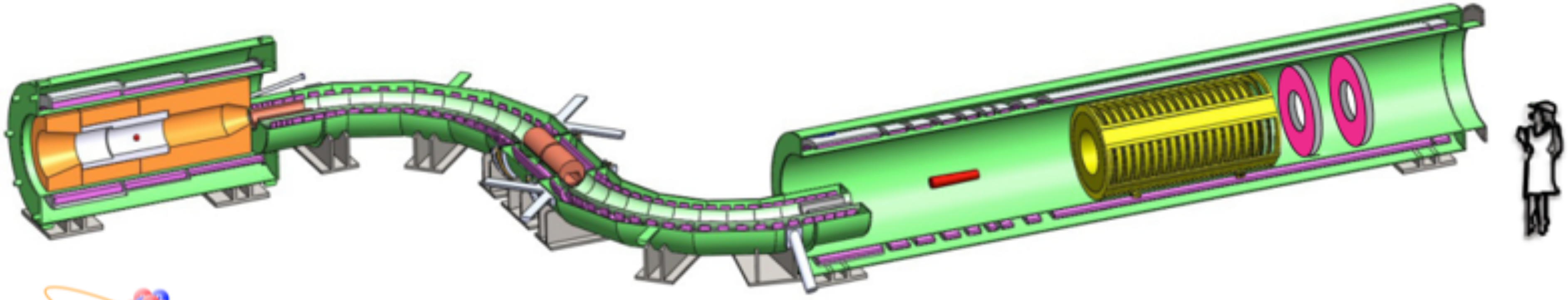
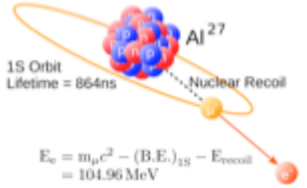
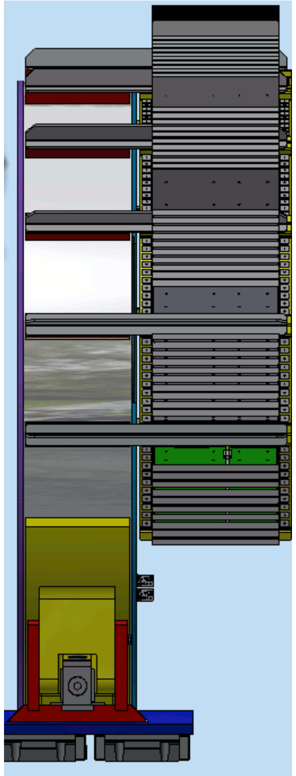
The Mu2e experiment @ FNAL





S. Miscetti, LNF INFN
1st lecture @
University
"La Sapienza"
Rome, Italy
19 January 2016



Lezione-1 Layout

- The CLFV processes
- The conversion process
- Physics Reach of Mu2e
- Mu2e experimental technique
- Mu2e Status

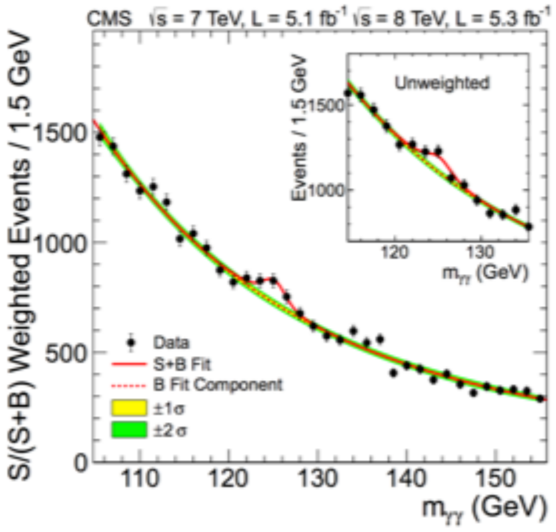
Introduction: SM

The Standard Model (SM) represents our better understanding of particles and forces (besides gravity) and it is very successful at describing a wide range of observations, but it does not explain yet:

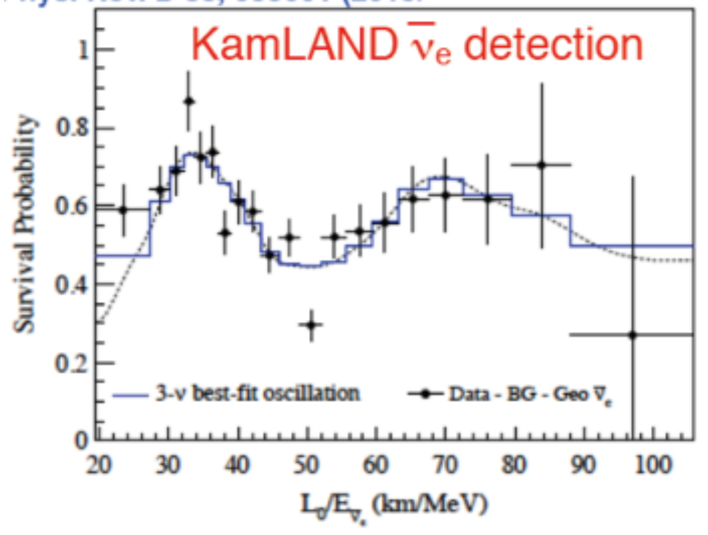
- number of generations
- Pattern of masses
- dark matter / dark energy
- prevalence of matter over antimatter
- …

And it doesn't account for neutrino mixing, which requires massive neutrinos (and which implies lepton number violation).

So there should be physics beyond the SM!



Phys. Rev. D 88, 033001 (2013)



Direct and indirect searches

We have not yet seen any unambiguous signal of physics beyond the SM.

Are we searching at the right places?
Are we looking at high enough energies?

We do not have the answer to these questions. So we should keep trying hard. Two methods are followed in HEP:

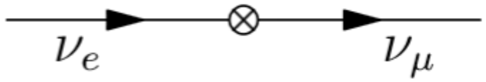
1. Direct searches at colliders (LHC), compelling but probe only relatively low mass scales, up to a few TeV

2. Indirect searches, probing masses far greater than those accessible at colliders, but requiring high precision measurements (e.g. $B_{s,d} \rightarrow \mu^+\mu^-$, Higgs couplings,…)

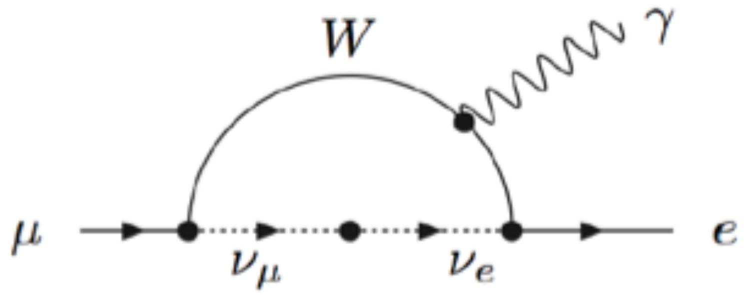
Among indirect searches, **charged lepton flavor violating** processes are particularly well suited to search for New Physics and study its structure.

Charged Lepton Flavour Violation

Neutral lepton flavor violation (i.e. neutrino mixing) implies charged lepton flavor violation (CLFV) through neutrino mixing.



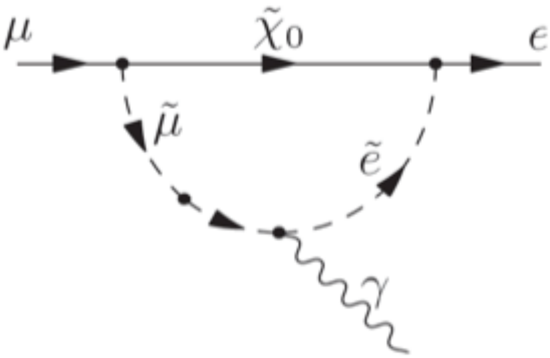
However, CLFV processes are strongly suppressed in the Standard Model.



BR($\mu \to e\,\gamma$) < 10^{-54} in the SM i.e. negligible.

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

New Physics can enhance CLFV rates to observable values.



Observation of CLFV is an unambiguous sign of New Physics

The big CLFV loop

Conversion

$\mu N \rightarrow eN$

Lepton decays

$\tau \rightarrow l\gamma,\ \tau \rightarrow lll,\ \tau \rightarrow lh$

$\mu \rightarrow e\gamma,\ \ \mu \rightarrow eee$

Collider (LHC)

$Z, Z' \rightarrow ll'$

SUSY, Exotic,…

Meson decays

$K,\ \phi,\ \ldots,\ B \rightarrow ll'$

Fixed target / EIC

$\mu N \rightarrow \tau N$

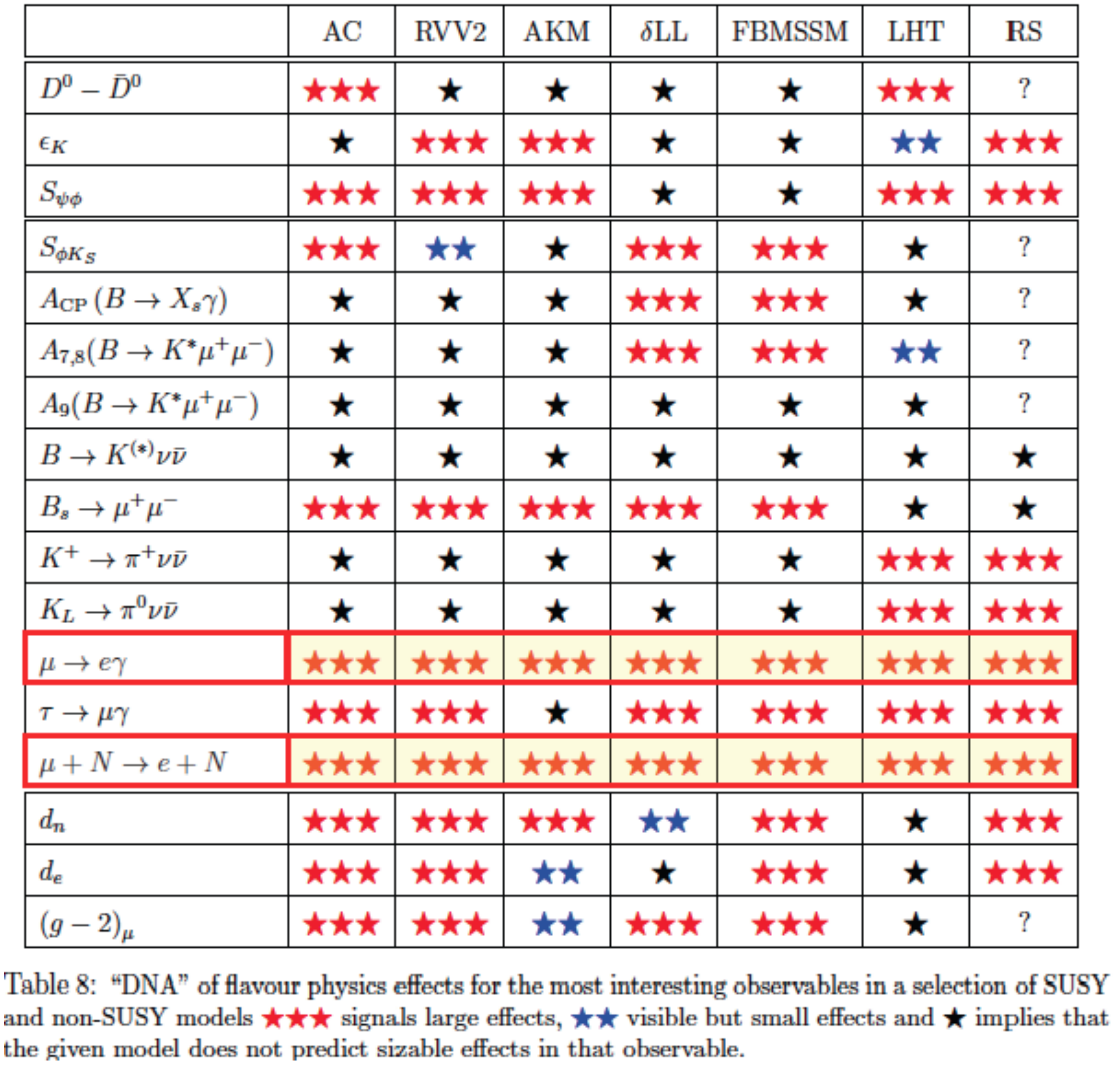
$eN \rightarrow \tau N$

CLFV

Lepton decays or conversions have a primary role in the CLFV processes …

Are CLFV processes relevant ?

W. Altmannshofer, *et al*, `arXiv:0909.1333 [hep-ph]`



	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

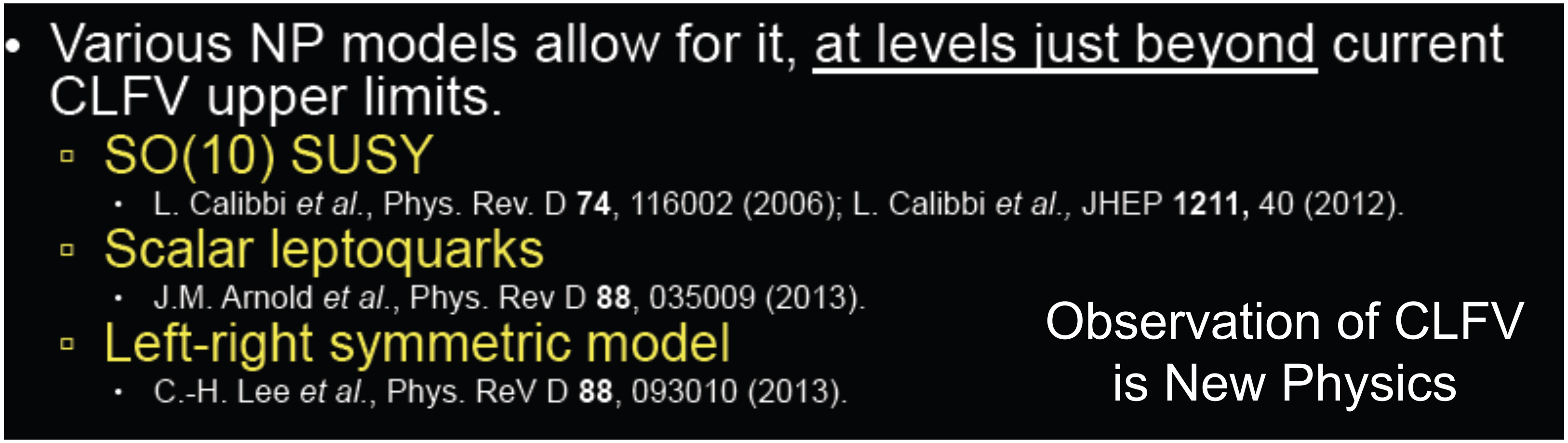
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

CLFV processes on muon sector

- Muon-to-electron conversion is a charged lepton flavor violating process (CLFV)

  similar but complementary to other CLFV processes as μ→ eγ andμ → 3 e.
- μ→ eγ is an in-flight decay searched @ PSI by the MEG (and now MEG-upgrade) experiment. It is leading the research in this field.
- Also μ → 3e is an experiment proposed @ PSI. It will be carried out

  in two phases for different reach in sensitivity (10^{-15}, 10^{-16})
- The Mu2e experiment @ FNAL (and COMET in Japan) searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \rightarrow e^- Al$

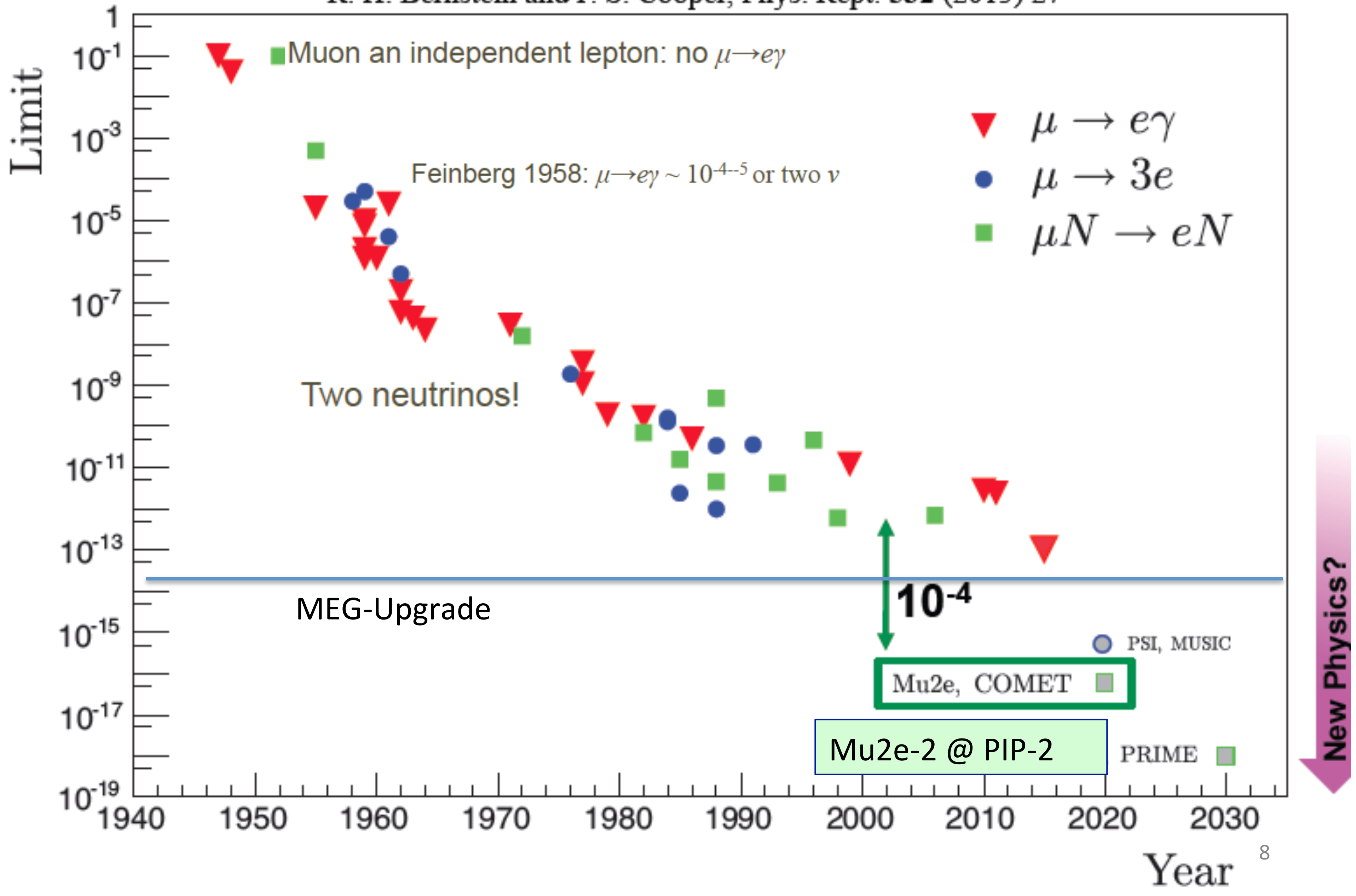


- Various NP models allow for it, at levels just beyond current CLFV upper limits.
  - SO(10) SUSY
    - L. Calibbi *et al.*, Phys. Rev. D **74**, 116002 (2006); L. Calibbi *et al.*, JHEP **1211,** 40 (2012).
  - Scalar leptoquarks
    - J.M. Arnold *et al.*, Phys. Rev D **88**, 035009 (2013).
  - Left-right symmetric model
    - C.-H. Lee *et al.*, Phys. ReV D **88**, 093010 (2013).

Observation of CLFV is New Physics

CLFV history

R. H. Bernstein and P. S. Cooper, Phys. Rept. **532** (2013) 27

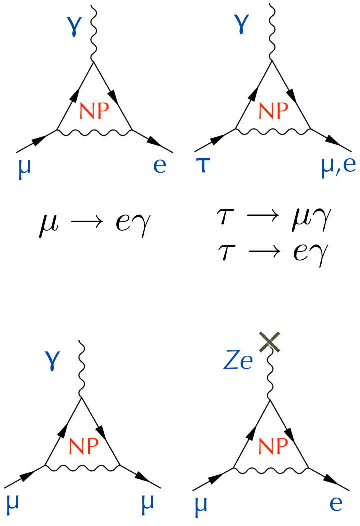


Mu2e vs MEG/MEG upgrade

$$L_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

LOOP TERM

$\kappa \ll 1$

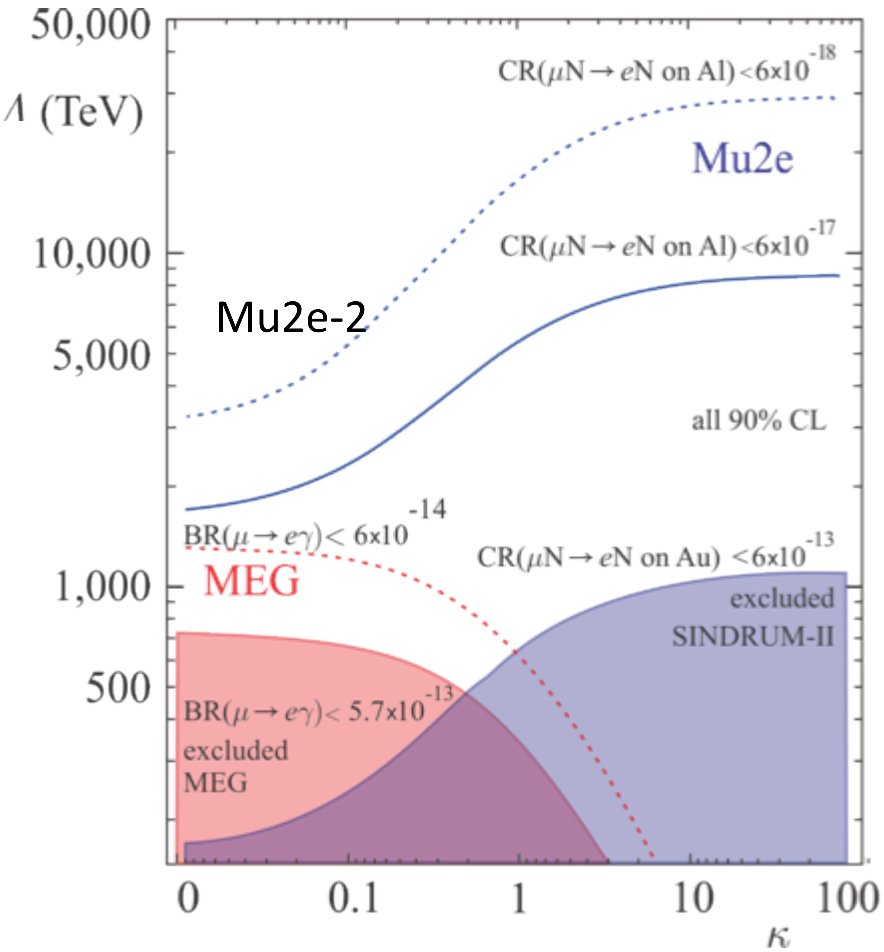


$\mu \to e\gamma$

$\tau \to \mu\gamma$
$\tau \to e\gamma$

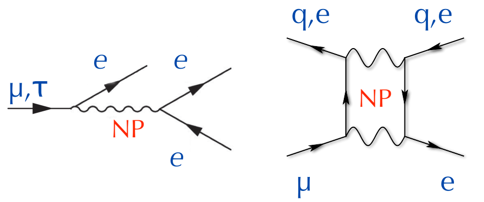
$(g-2)_\mu$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$



CONTACT TERM

$\kappa \gg 1$



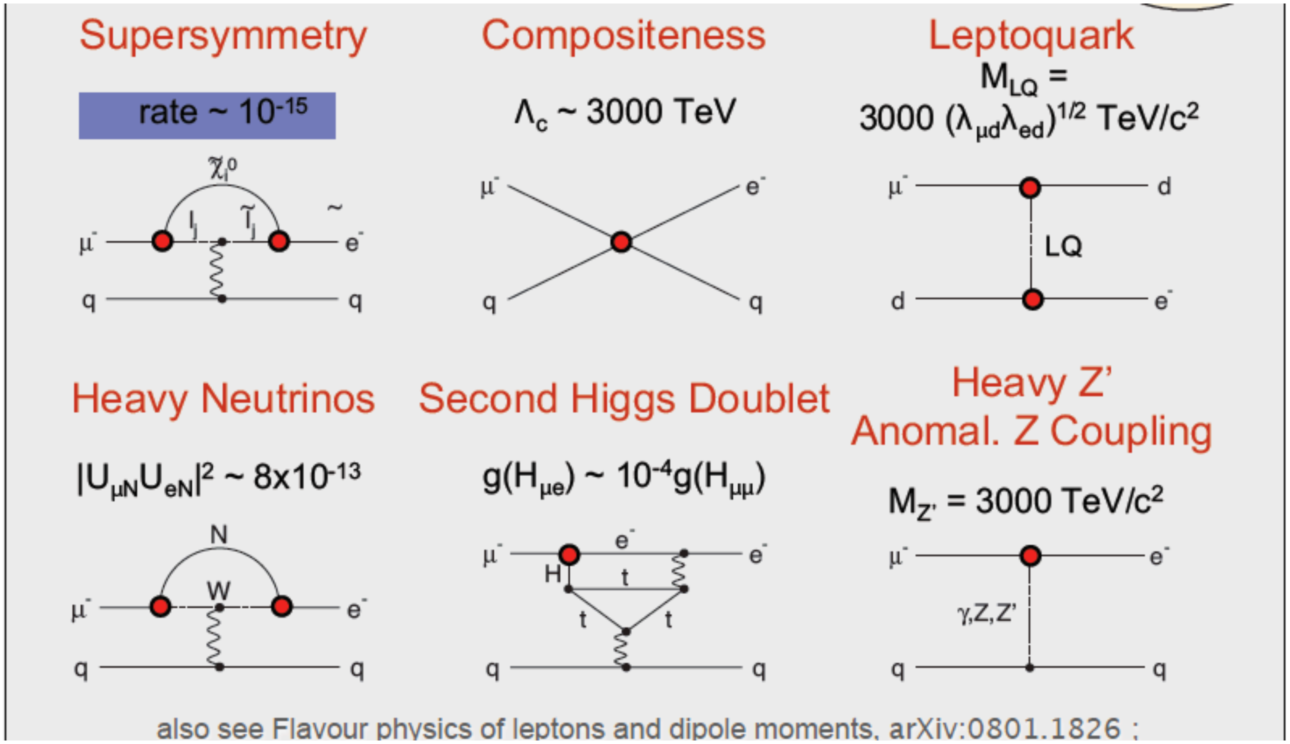
$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

Mu2e physics reach & goal

Sensitivity reach:
10^4 improvement with respect to previous μ to electron conversion experiment (Sindrum-II) by means of 4 handles:

→ Rate (Intensity)
→ Out of Time extinction
→ Delayed gate
→ Precise Resolution

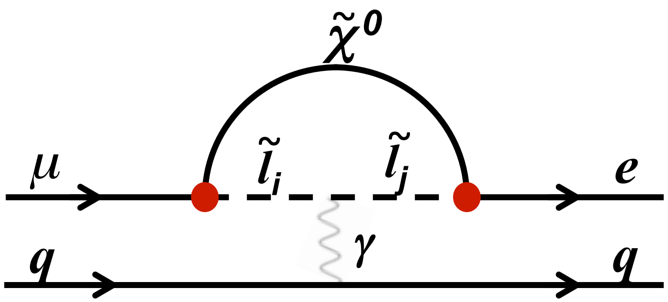


also see Flavour physics of leptons and dipole moments, arXiv:0801.1826 ;

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \to e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \to \text{ all muon capture})} \leq 6\times 10^{-17}\ (@90\%\text{CL})$$

Specific Example: SUSY

Probe SUSY through loops

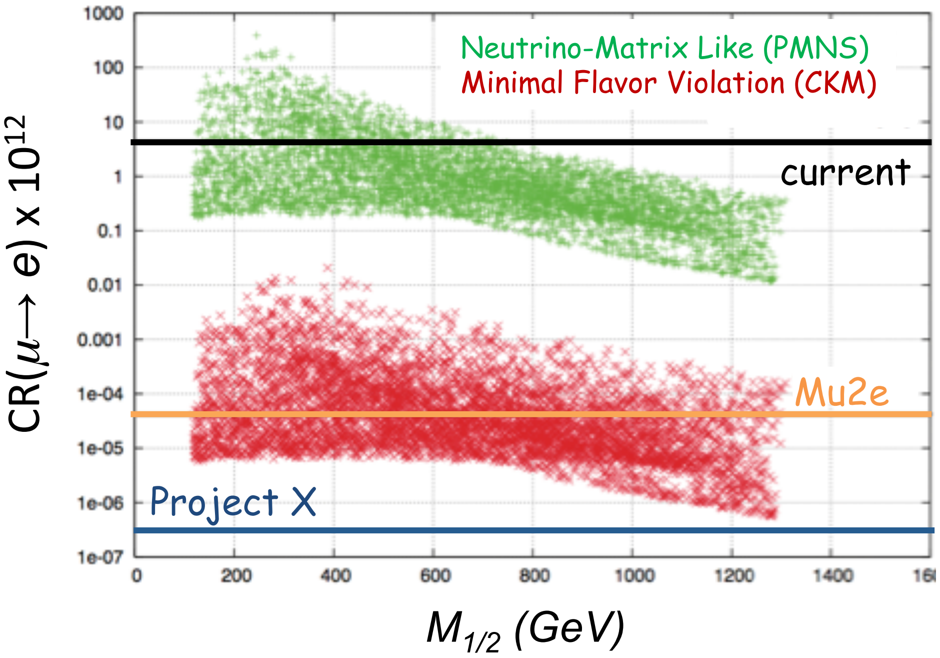


If SUSY seen at LHC → rate ~10^{-15}

Implies O(40) reconstructed signal events with negligible background in Mu2e for many SUSY models.

SUSY GUT in an SO(10) framework

$\mu N \to eN$ (tanβ = 10)



L. Calibbi et al., hep-ph/0605139

Complementary with the LHC experiments while providing models' discrimination

SUSY benchmark points vs LHC

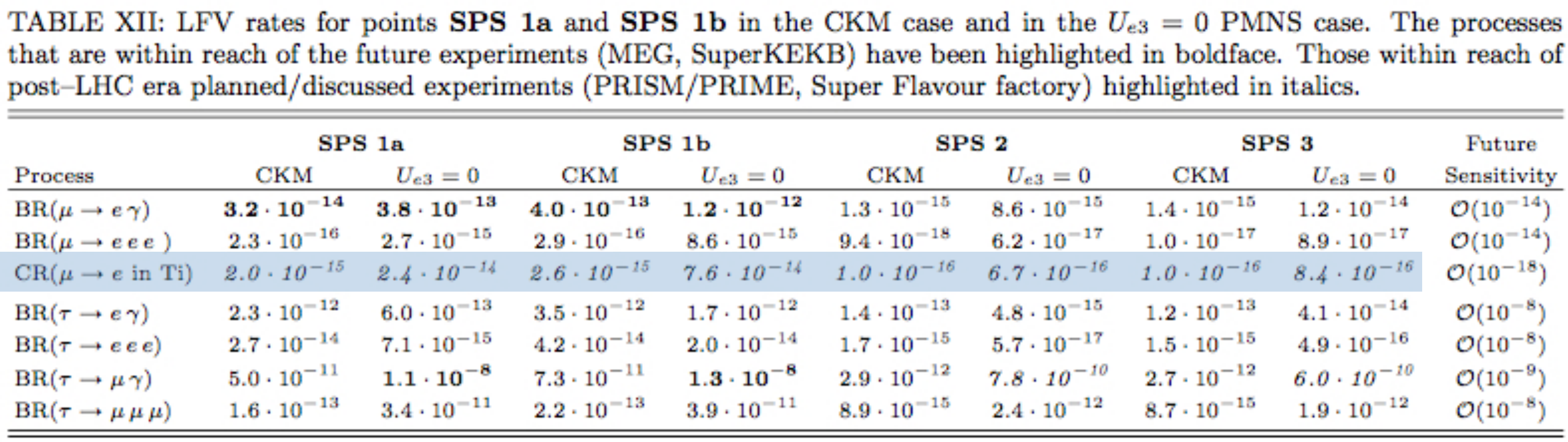


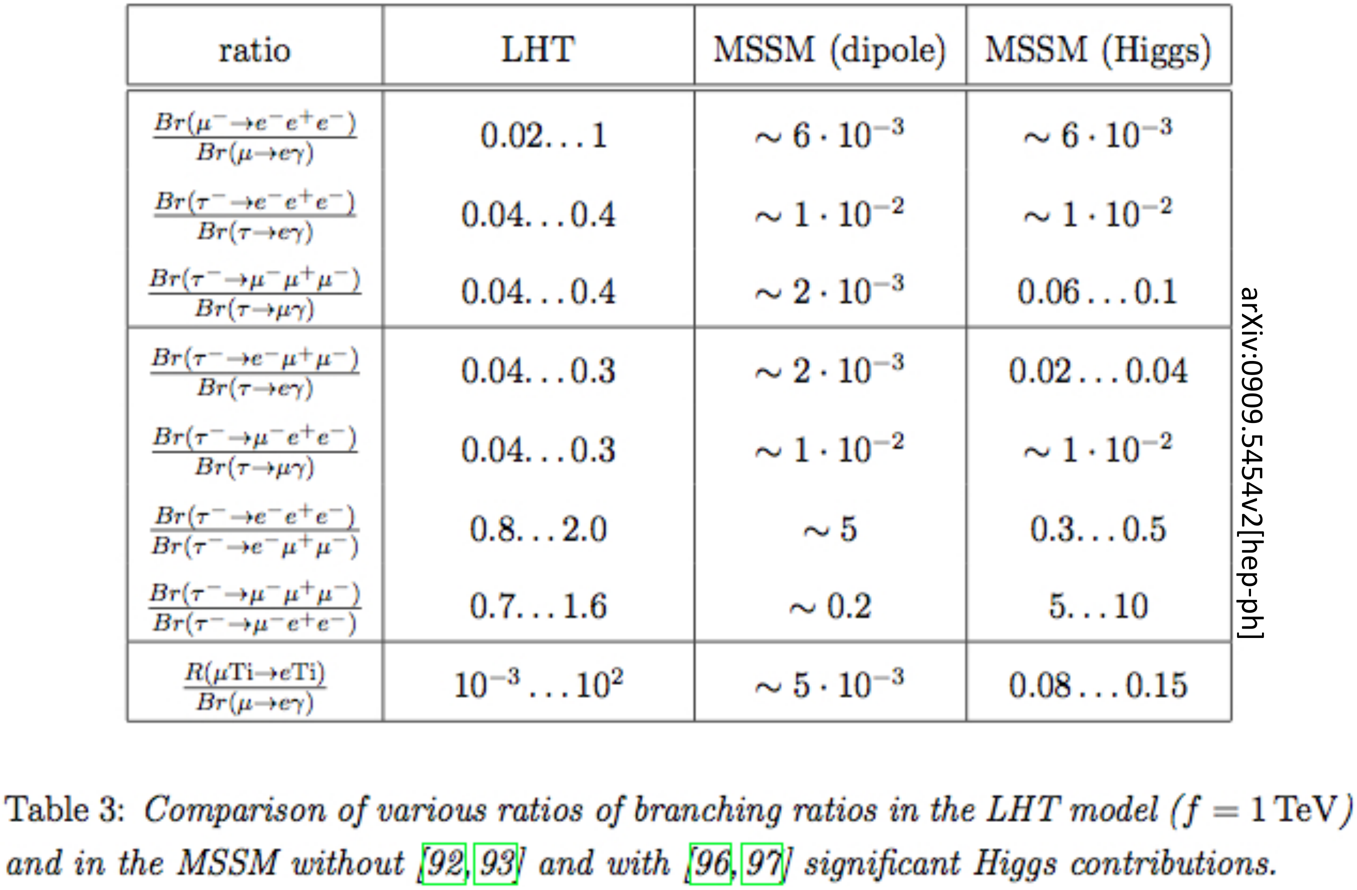
TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

	SPS 1a		**SPS 1b**		**SPS 2**		**SPS 3**		Future
Process	CKM	$U_{e3} = 0$	CKM	$U_{e3} = 0$	CKM	$U_{e3} = 0$	CKM	$U_{e3} = 0$	Sensitivity
$\mathrm{BR}(\mu \to e\,\gamma)$	**$3.2 \cdot 10^{-14}$**	**$3.8 \cdot 10^{-13}$**	**$4.0 \cdot 10^{-13}$**	**$1.2 \cdot 10^{-12}$**	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$\mathrm{BR}(\mu \to e\,e\,e\,)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$\mathrm{CR}(\mu \to e \text{ in Ti})$	*$2.0 \cdot 10^{-15}$*	*$2.4 \cdot 10^{-14}$*	*$2.6 \cdot 10^{-15}$*	*$7.6 \cdot 10^{-14}$*	*$1.0 \cdot 10^{-16}$*	*$6.7 \cdot 10^{-16}$*	*$1.0 \cdot 10^{-16}$*	*$8.4 \cdot 10^{-16}$*	$\mathcal{O}(10^{-18})$
$\mathrm{BR}(\tau \to e\,\gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to e\,e\,e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,\gamma)$	$5.0 \cdot 10^{-11}$	**$1.1 \cdot 10^{-8}$**	$7.3 \cdot 10^{-11}$	**$1.3 \cdot 10^{-8}$**	$2.9 \cdot 10^{-12}$	*$7.8 \cdot 10^{-10}$*	$2.7 \cdot 10^{-12}$	*$6.0 \cdot 10^{-10}$*	$\mathcal{O}(10^{-9})$
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SUSY benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/Belle-2
- All of these will be observable by Mu2e

Other CLFV Predictions

M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino



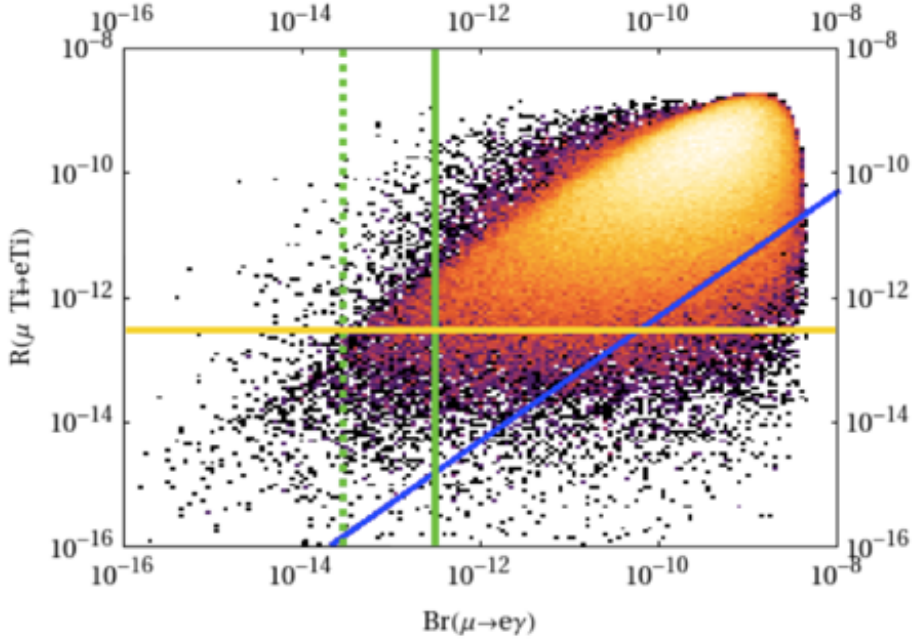
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

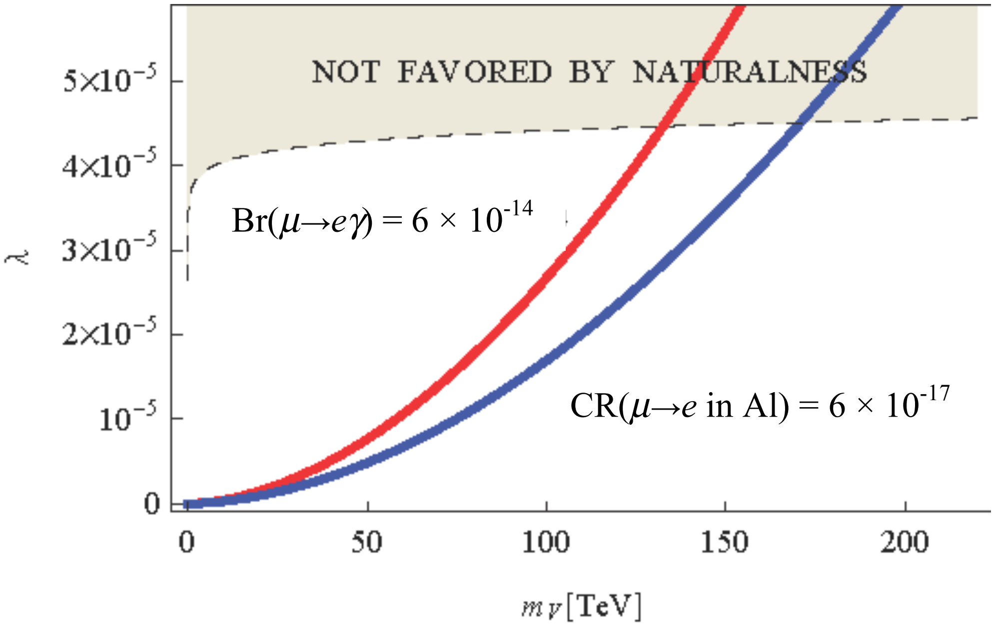
arXiv:0909.5454v2[hep-ph]

- **Relative rates are model dependent**
- **Measure ratios to pin-down theory details**

MU2E vs MEG-upgrade



Littlest Higgs model with T-parity



Leptoquarks

- Yellow line, limit by SINDRUM-II
- Grenn lines, MEG and MEG-upgrade
- Mu2e covers all parameter space

- Red line → MEG-upgrade
- Blue line → MU2E

Summary: why Mu2e is unique?

Muon to electron conversion is a unique probe for BSM:

◆ **Broad discovery sensitivity across all models:**

→ Sensitivity to the same physics of MEG but with better mass reach

→ Sensitivity to physics that MEG is not

→ If MEG observes a signal, MU2E does it with improved statistics.
Ratio of the BR allows to pin-down physics model

→ If MEG does not observe a signal, MU2E has still a reach to do so.
In a long run, it can also improve further with the proton improvement plan (PIP-2) at FNAL

◆ **Sensitivity to λ (mass scale) up to hundreds of TeV beyond any current existing accelerator**

The conversion process and the experimental Technique

Experimental Technique (1)

Experimental concept to search for muon-to-electron conversion

- Produce muons via protons hitting a fixed target:
  p + nucleus $\rightarrow \pi^- \rightarrow \mu^- \nu_\mu$

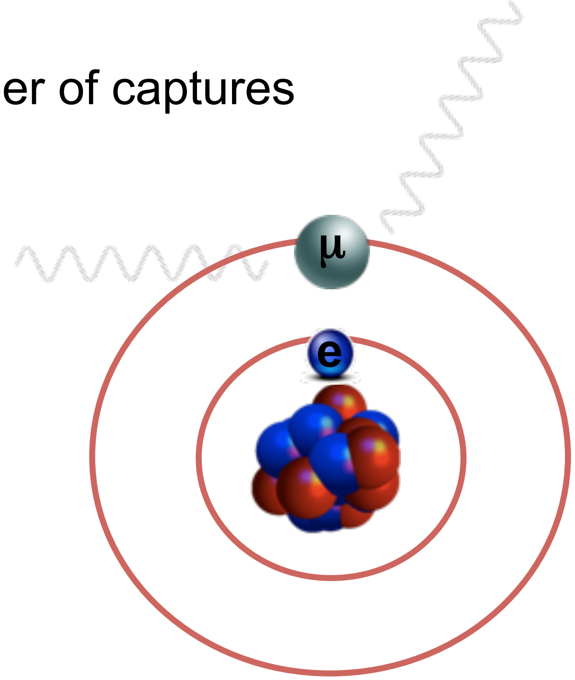
- Collect and stop low momentum muons in atoms
  Aluminum target for Mu2e

- Muon cascade to K shell (~ps) firing off X rays
  measure X rays spectrum to estimate the number of captures

- Wait for muon to convert into electron
  for Al, $t_m^{Al} = 864$ ns

- Signal is a mono-energetic electron

$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\rm recoil} \\ &= 104.973 \text{ MeV} \quad \text{(for Al)} \end{aligned}$$



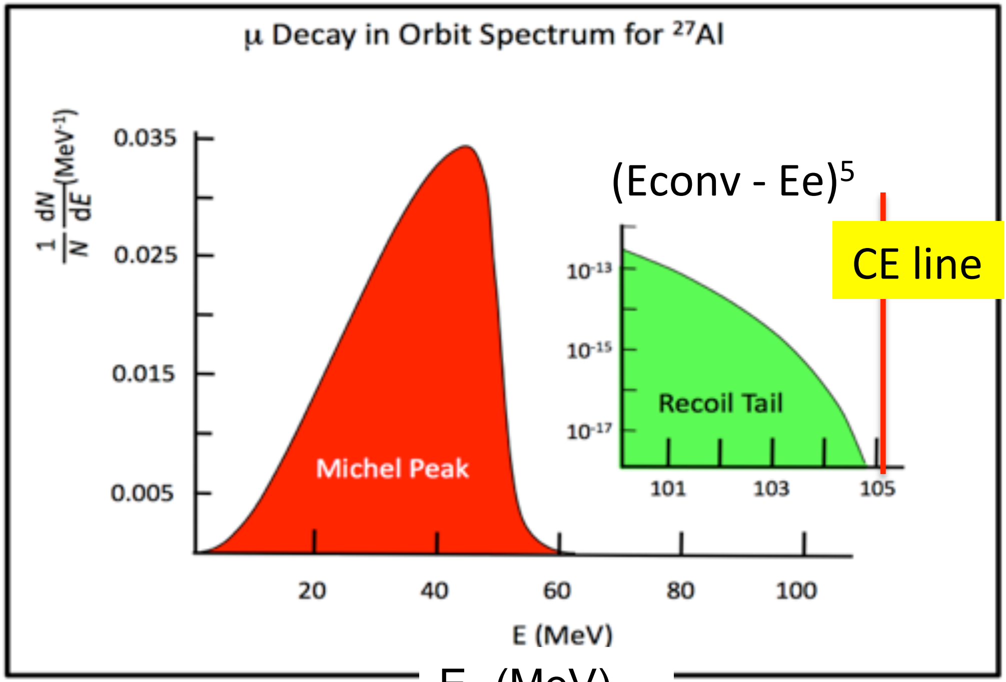
Experimental Technique (2)

Nuclear capture (~61% for Al)

$$\mu N \rightarrow \nu_\mu N'^*$$

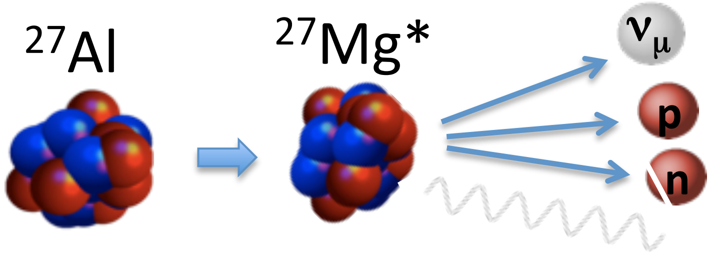
Muon decay in orbit (~39% for Al)

$$\mu \rightarrow e\, \nu_\mu \nu_e$$

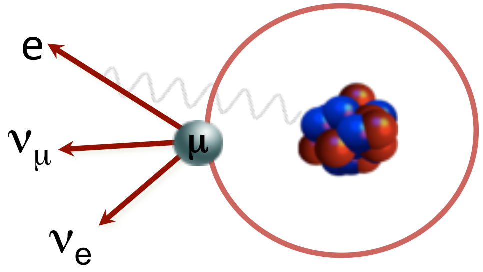


E_e (MeV)

Czarnecki et al., Phys. Rev. D 84, 013006 (2011) arXiv: 1106.4756v2



Decay products could produce electrons and pile-up with the signal. Neutrons provide a source of irradiation on Detectors



The Michel spectrum is distorted by the presence of the nucleus and the electron can be at the conversion energy if the neutrinos are at rest

To separate DIO from CE-line, we need a high resolution spectrometer

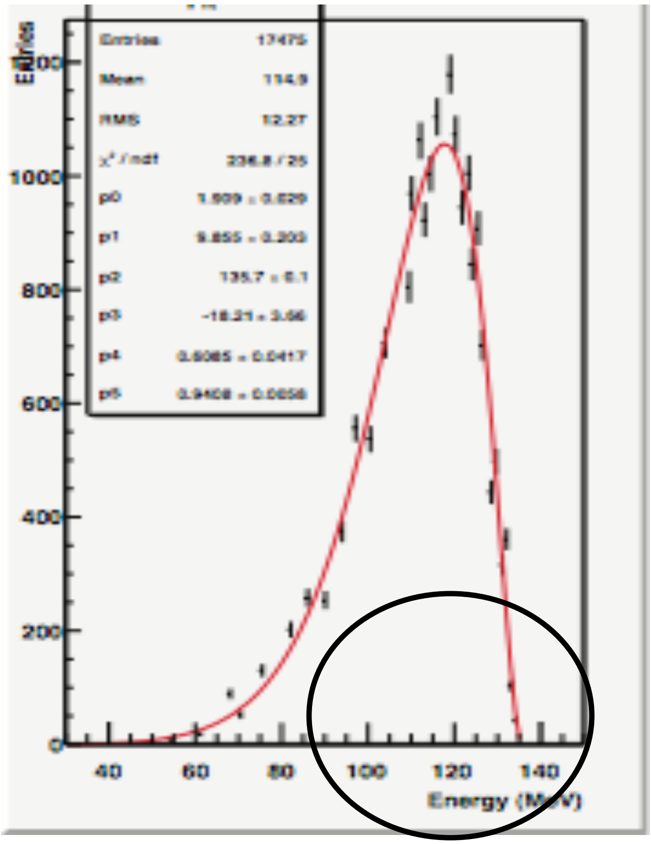
Other backgrounds

Prompt background

Particles produced in addition to the muons by primary protons which interact almost immediately when they hit the stopping target: pions, neutrons, antiprotons.

- Radiative pion capture (RPC)
  $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$
  $\pi^- N \rightarrow e^+e^- N'$
- Pion/muon decays in flight

Photon energy spectrum from radiative pion capture in Mg



Other background

- Antiprotons producing pions when annihilating in the target
- Cosmic rays induced,…

Sindrum-II

W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

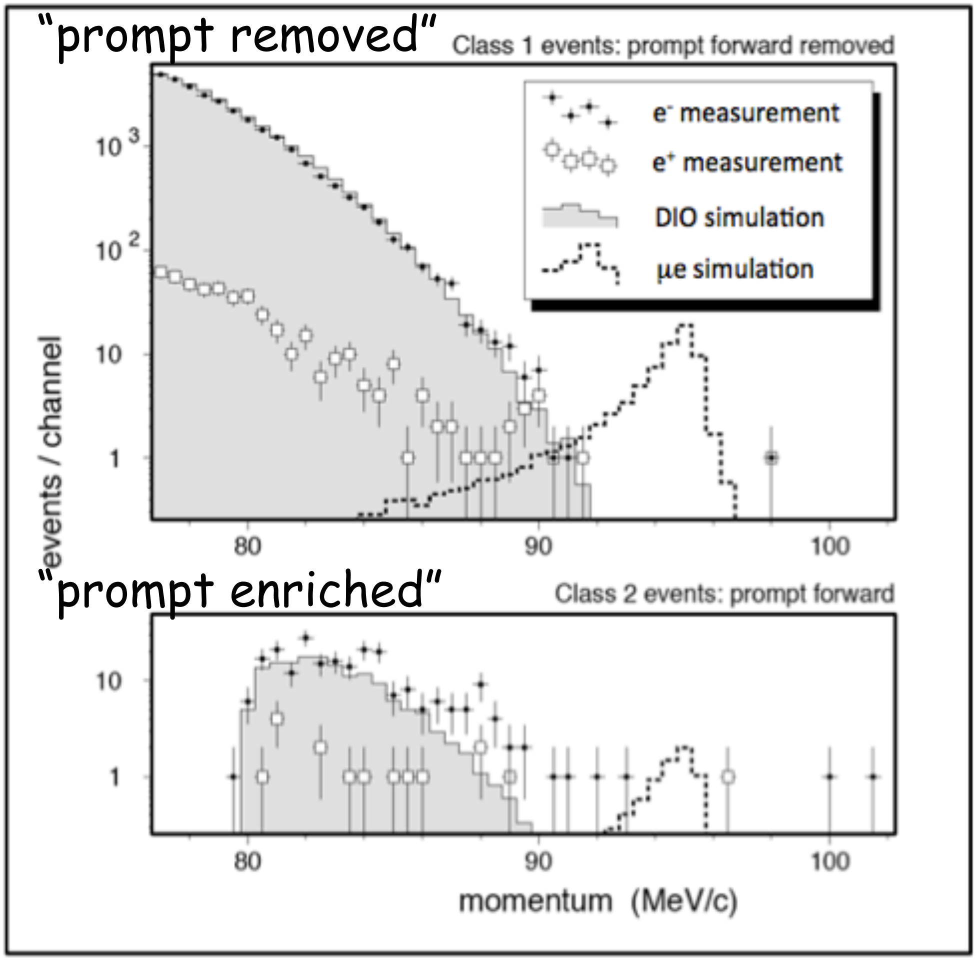
SINDRUM II @ PSI

Final results on Au:

$R_{\mu e} < 7\times10^{-13}$ @ 90% CL

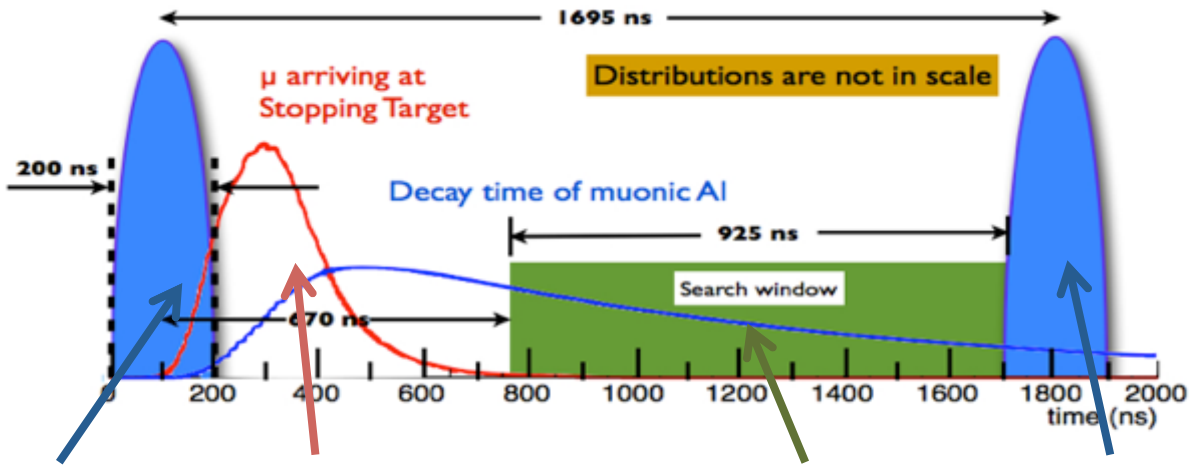
One candidate event past the end of the spectrum. Pion capture, cosmic ray?

Timing cut shows the contribution of prompt background (0.3 ns muon pulse separated by 20 ns)



How can we improve ???

Beam structure → prompt background



Beam hits target

Prompt bkg like radiative pion capture

Mainly Decay In Orbit background

Next bunch

Need a pulsed beam to wait for prompt background to reach acceptable levels!

- ☐ RPC = Radiative Pion Capture ($\pi^- N \rightarrow \gamma N$), e$^-$ in the beam,
- ☐ decay in flight of muons/pions

FNAL accelerator provides the right beam

To summarize .....

Muons

Need a lot of muons, more than a factor 1000 increase in muon intensity compared to SINDRUM.

Pulsed beam / Extinction / Solenoids

- Wait period between bunches to suppress prompt background like Radiative Pion Capture.
- Number of protons between bunches must be $< 10^{-10}$.
- Need capture solenoid around target to get the desired muon flux

Detector

Excellent detector capabilities to measure the electron energy to reject DIO background

The Mu2e experiment

The Mu2e experiment

Mu2e Collaboration

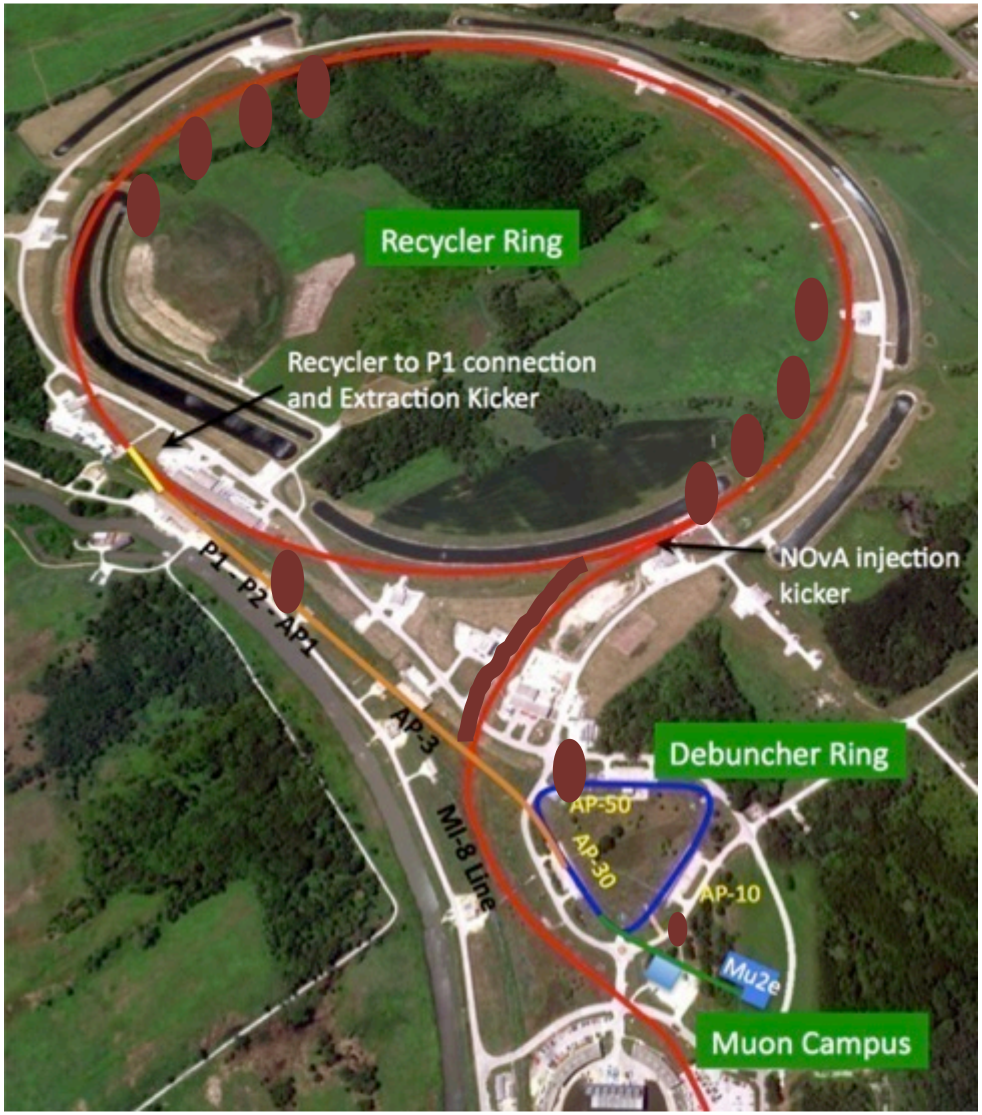
Mu2e Collaboration 2013

- ~ 200 Collaborators, 32 Institutions, 3 +2 Countries
- Still growing. Discussion with several USA university groups.
- **2 UK groups joining: UCL and Liverpool**
- **HZDR (Dresda)**

Dresda groups joined @ April 2015, UK in 2016

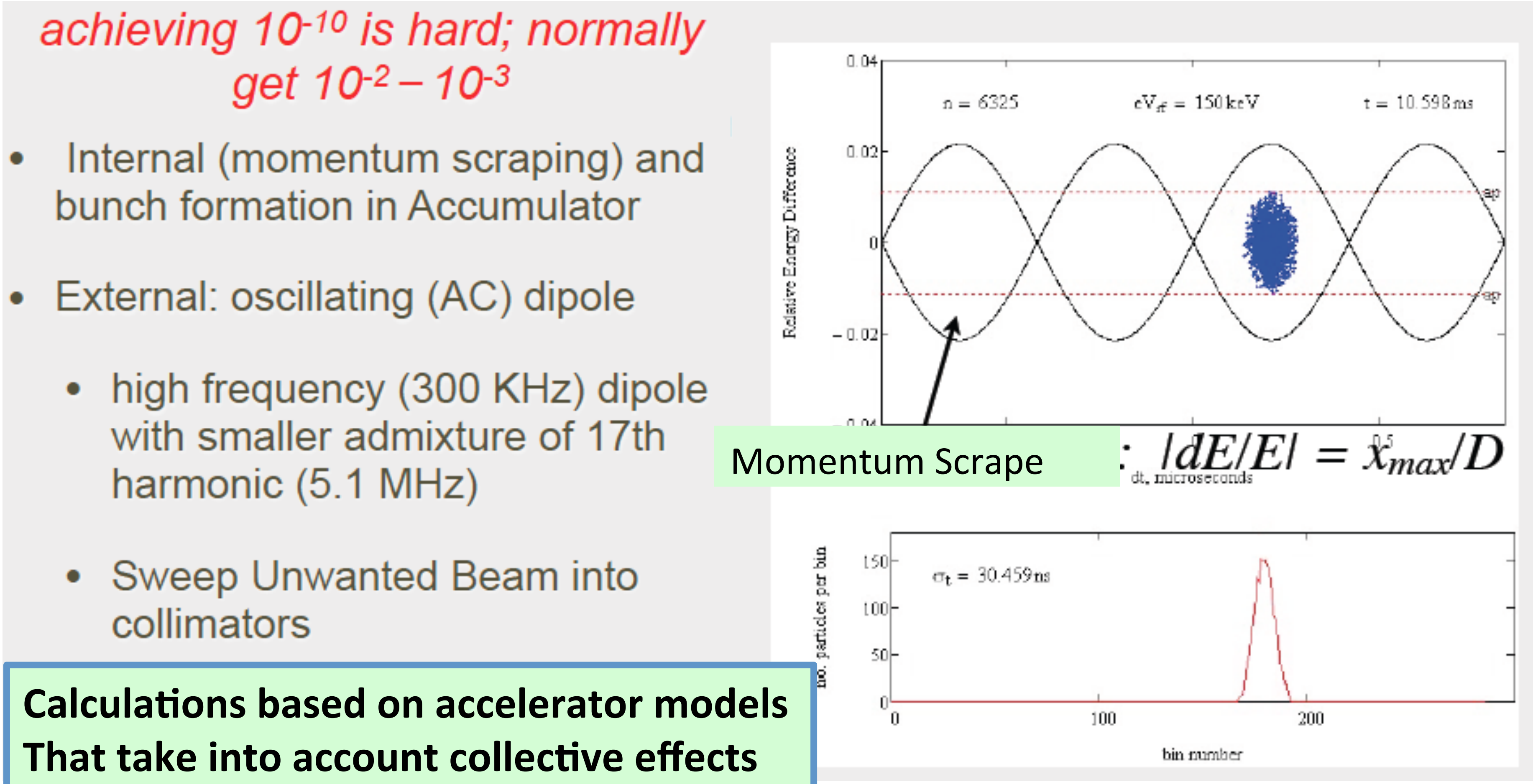
Accelerator Scheme

- Booster: batch of 4×10^{12} protons every 1/15th second
- Booster "batch" is injected into the Recycler ring
- Batch is re-bunched into 4 bunches
- These are extracted one at a time to the Debuncher/Delivery ring
- As a bunch circulates, protons are extracted to produce the desired beam structure
- **Produces bunches of ~3x10^7 protons each, separated by 1.7 μs (debuncher ring period)**



Out of Time proton → Extinction Method

Proton extinction between pulses → # protons out of beam/# protons in pulse



achieving 10^{-10} is hard; normally get $10^{-2} - 10^{-3}$

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators

Momentum Scrape $: |dE/E| = x_{max}/D$

Calculations based on accelerator models
That take into account collective effects
Shows that this combination gets ~ 10^{-12}

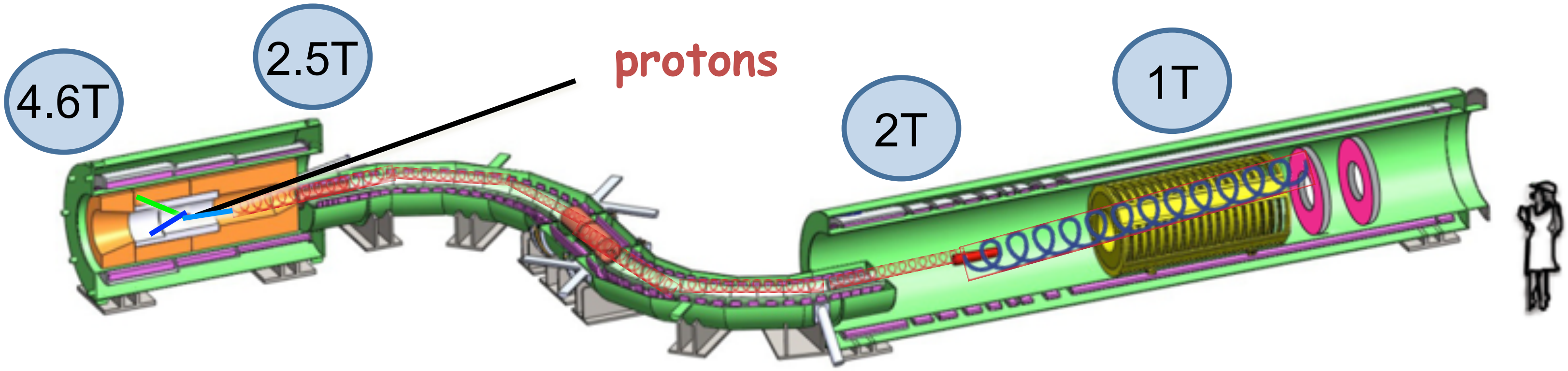
The Muon Campus

SOLENOIDS

Muon Beam-line

Production Target / Solenoid (PS)

- 8 GeV Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons



Transport Solenoid (TS)

Selects low momentum, negative muons
Antiproton absorber in the mid-section

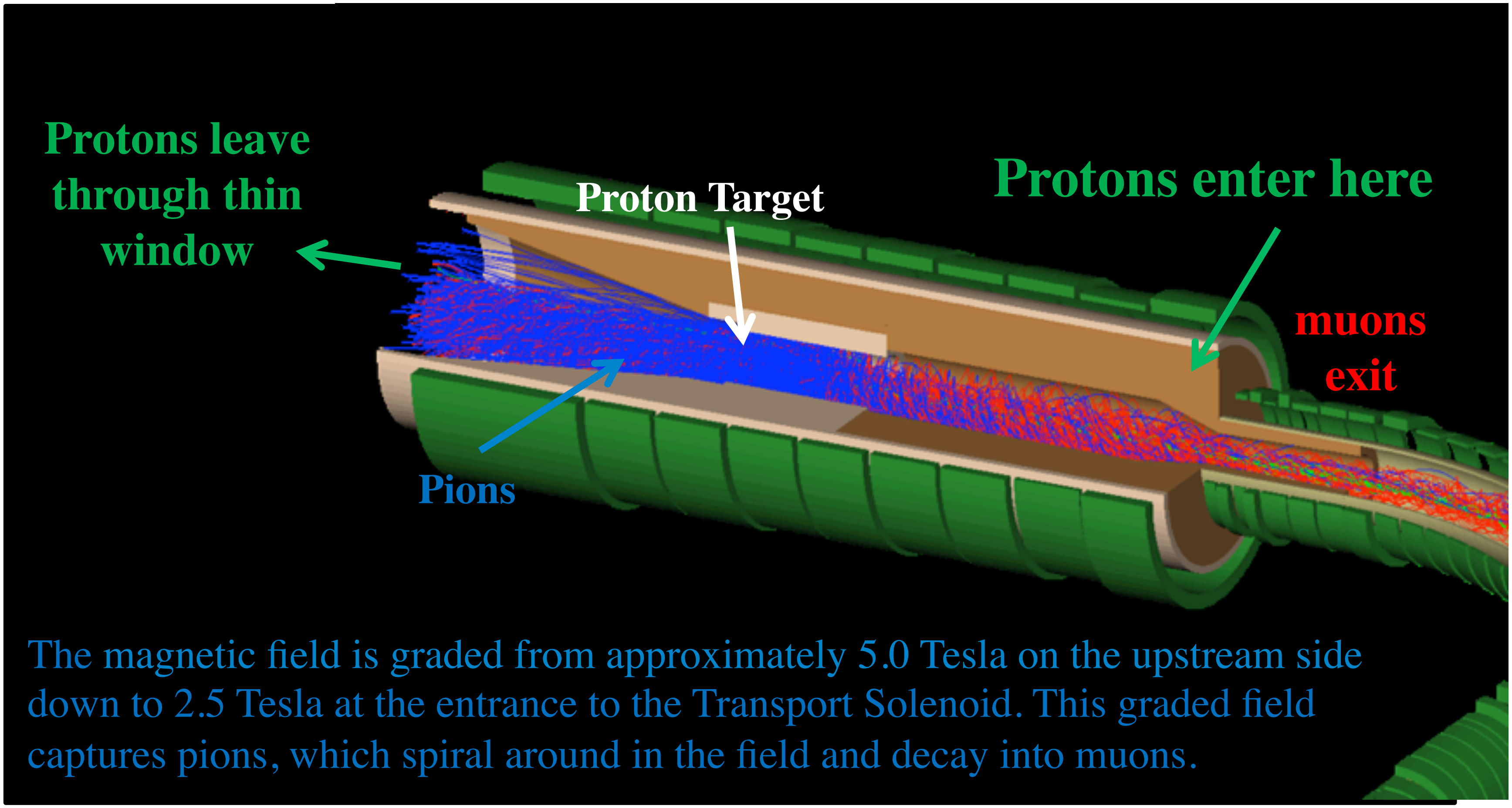
Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field "reflects" downstream conversion electrons emitted upstream (isotropic process)

For the sensitivity goal → ~ 6 x 10^{17} stopped muons with 3 year run , 6 x 10^7 sec → 10^{10} stopped muon/sec

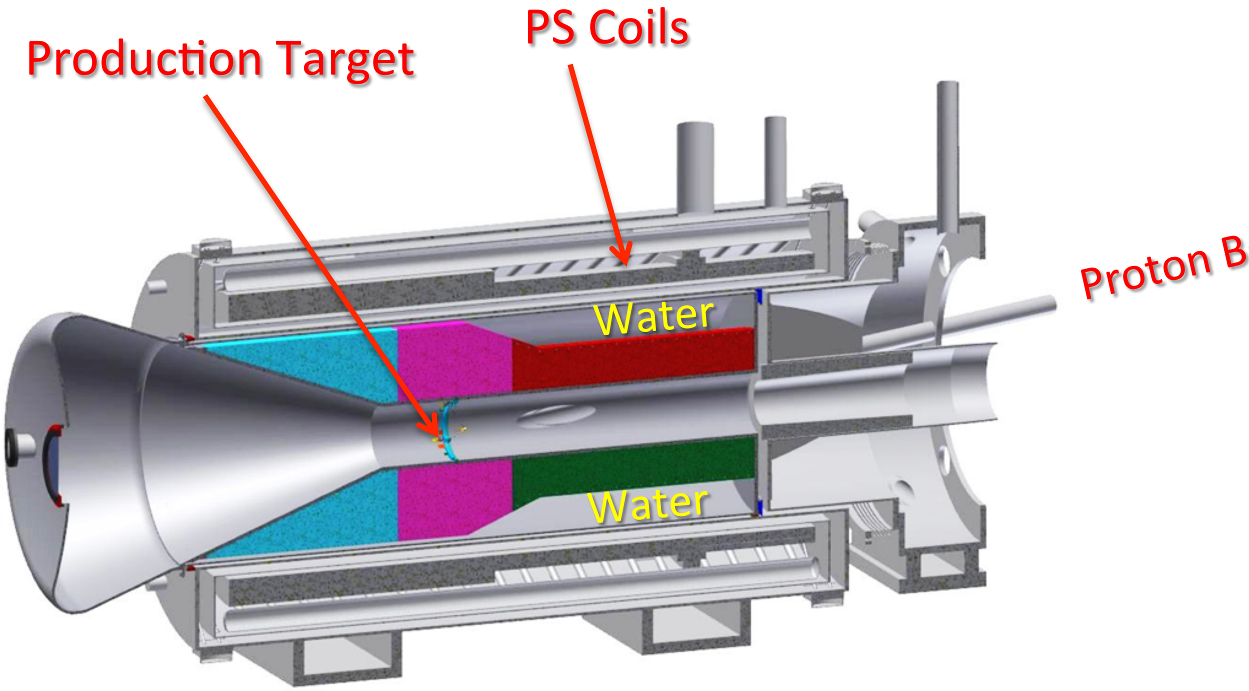
Production Solenoid

Protons enter opposite to outgoing muons:
This is a central idea to remove prompt background

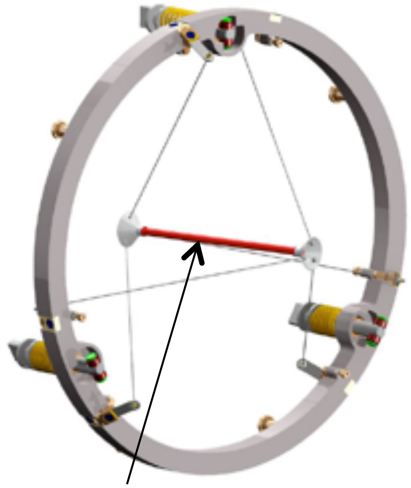


The magnetic field is graded from approximately 5.0 Tesla on the upstream side down to 2.5 Tesla at the entrance to the Transport Solenoid. This graded field captures pions, which spiral around in the field and decay into muons.

PS details



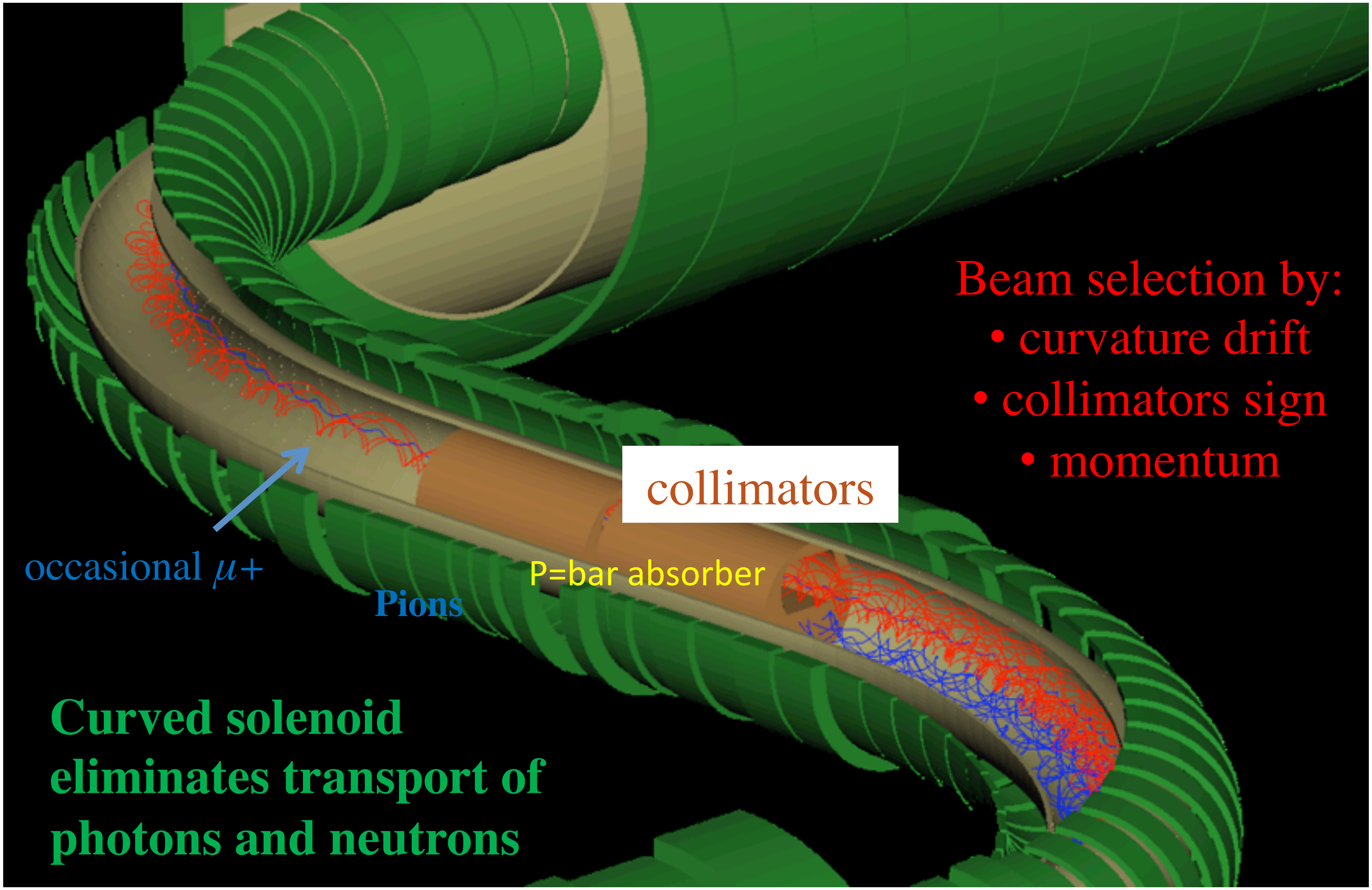
Production Target assembly



Tungsten target

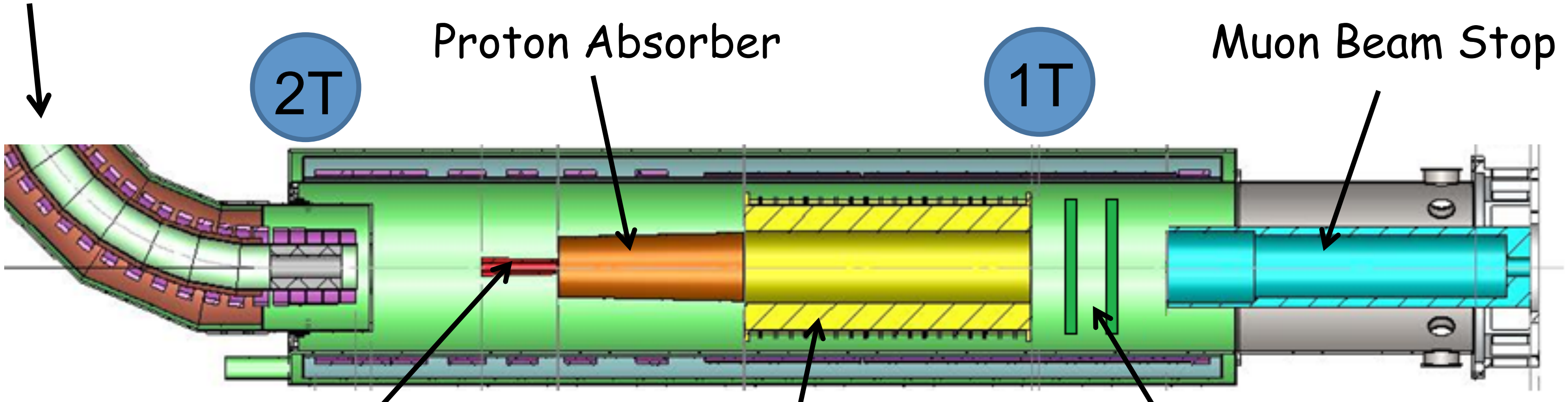
- “Bunch/Pulse” of protons delivered every 1695 ns
- Protons on production target produce a spray of particles
  - Highest energy escape to beam dump. Low energy reflected by magnetic field gradient, swept downstream

Transport Solenoid



Detector Solenoid

Graded field "reflects" downstream a fraction of conversion electrons emitted upstream



2T

Proton Absorber

1T

Muon Beam Stop

muon stopping target

Tracker

EM Calorimeter

17 Al foils; Aluminum selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the prompt separation in the Mu2e beam structure.

For the sensitivity goal → ~ 6 x 10^{17} stopped muons

For 3 year run , 6 x 10^{7} sec → 10^{10} stopped muon/sec (10 GHz)

Stopping Target

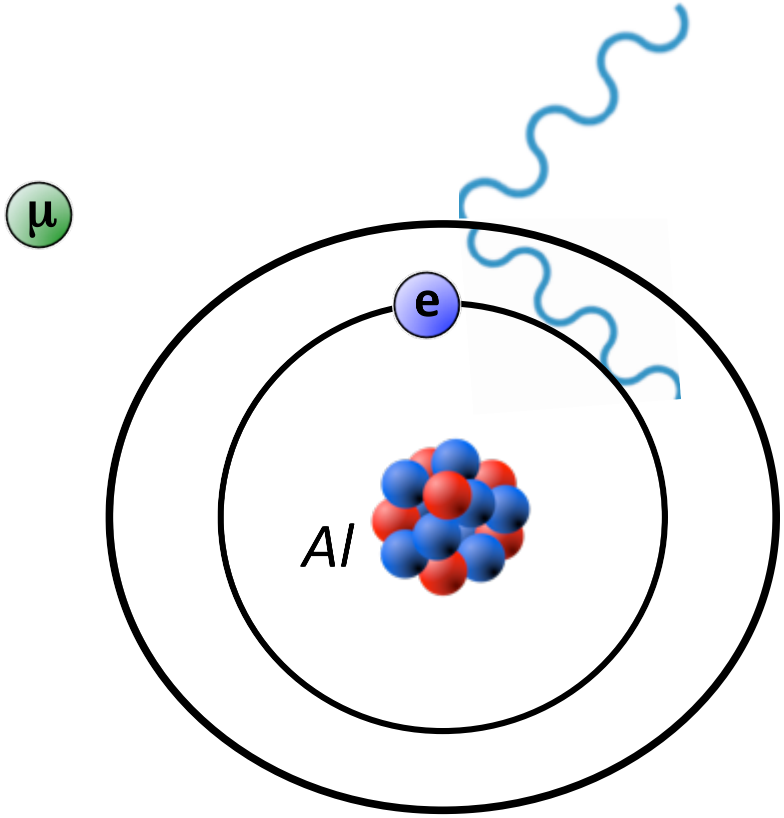
Stopping Target:

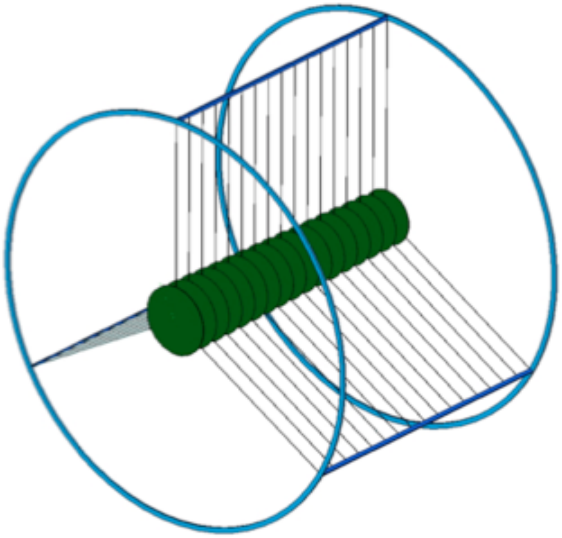
17 Thin (200 micron thick) Al foils

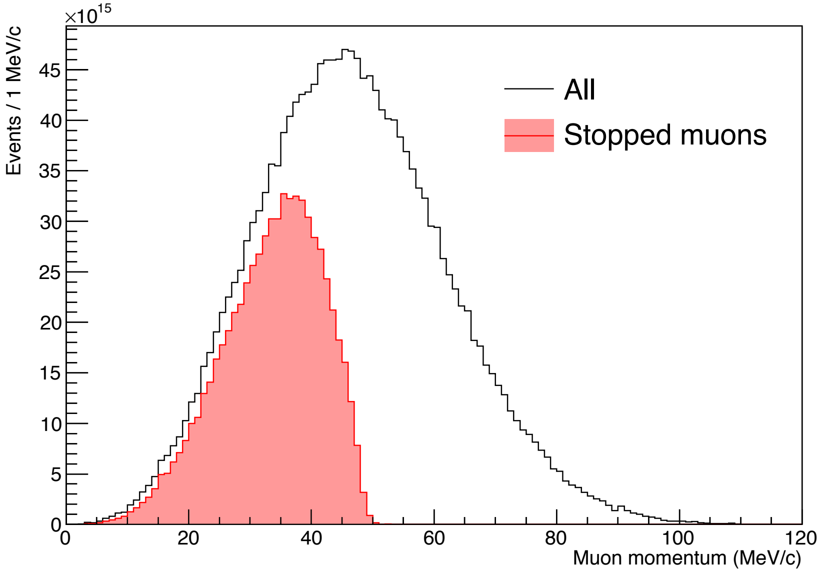
5 cm spacing

From 10 cm to 6 cm radius

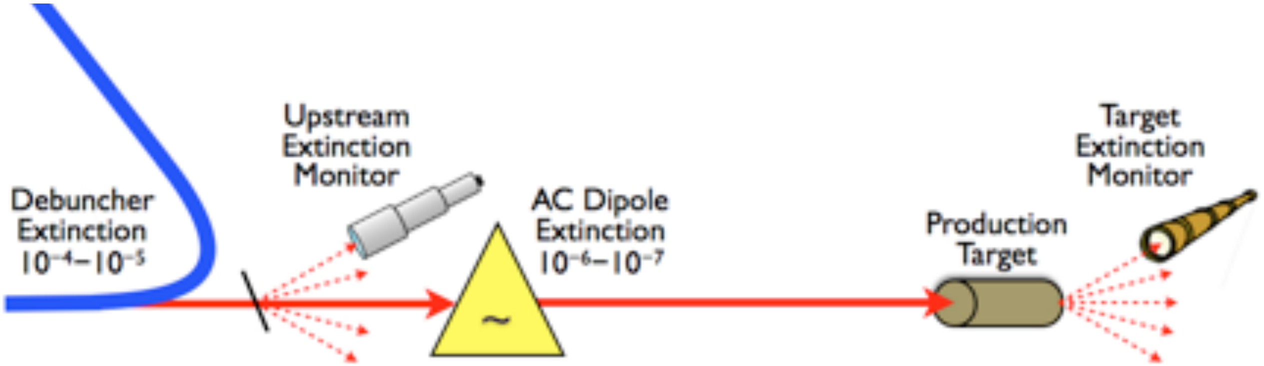
This is where this happens







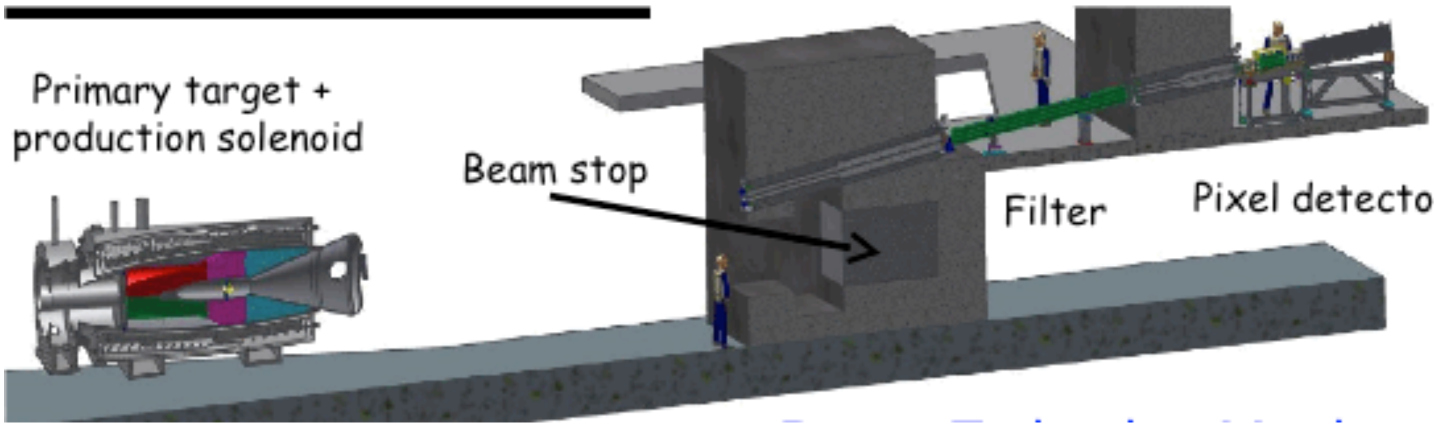
Extinction monitor



- Thin foils in the debuncher → Mu2e production target transport line (fast feedback)
- Off-axis telescope looking at the production target (slow feedback – timescale of hours)

Spectrometer based on ATLAS pixel detector

Reach a 10^{-10} extinction sensitivity in an hour or so



Stopping monitor

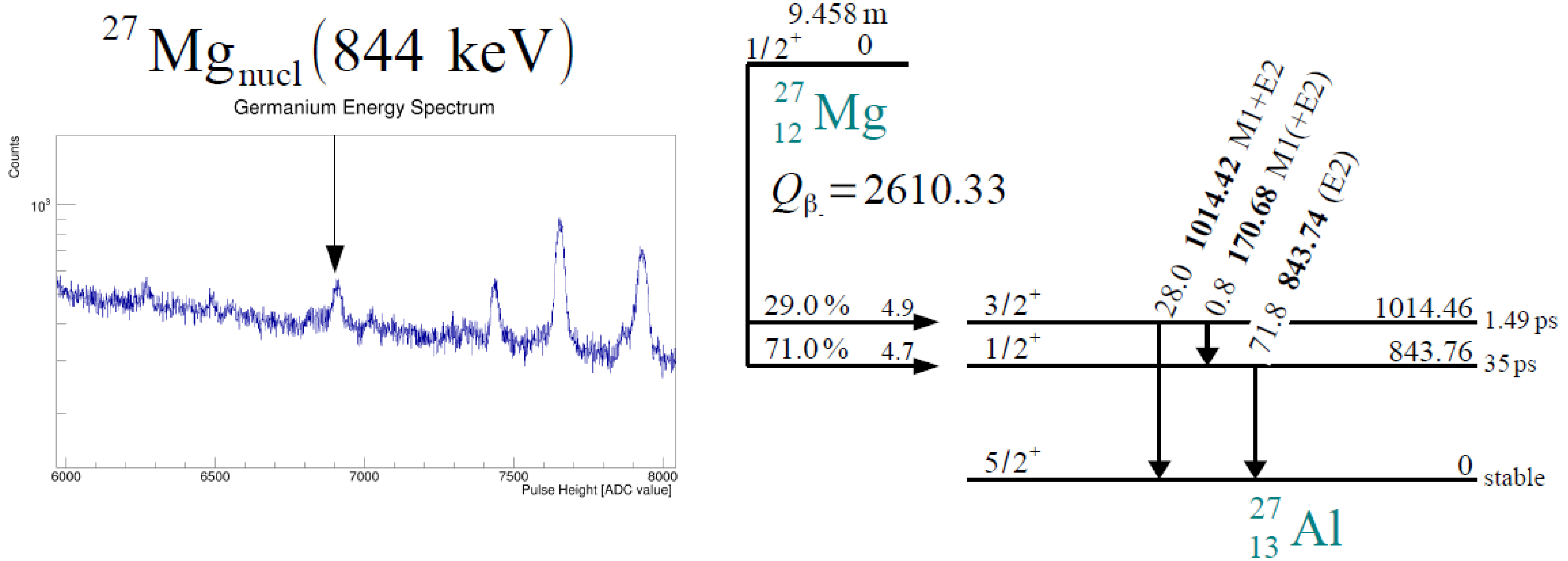
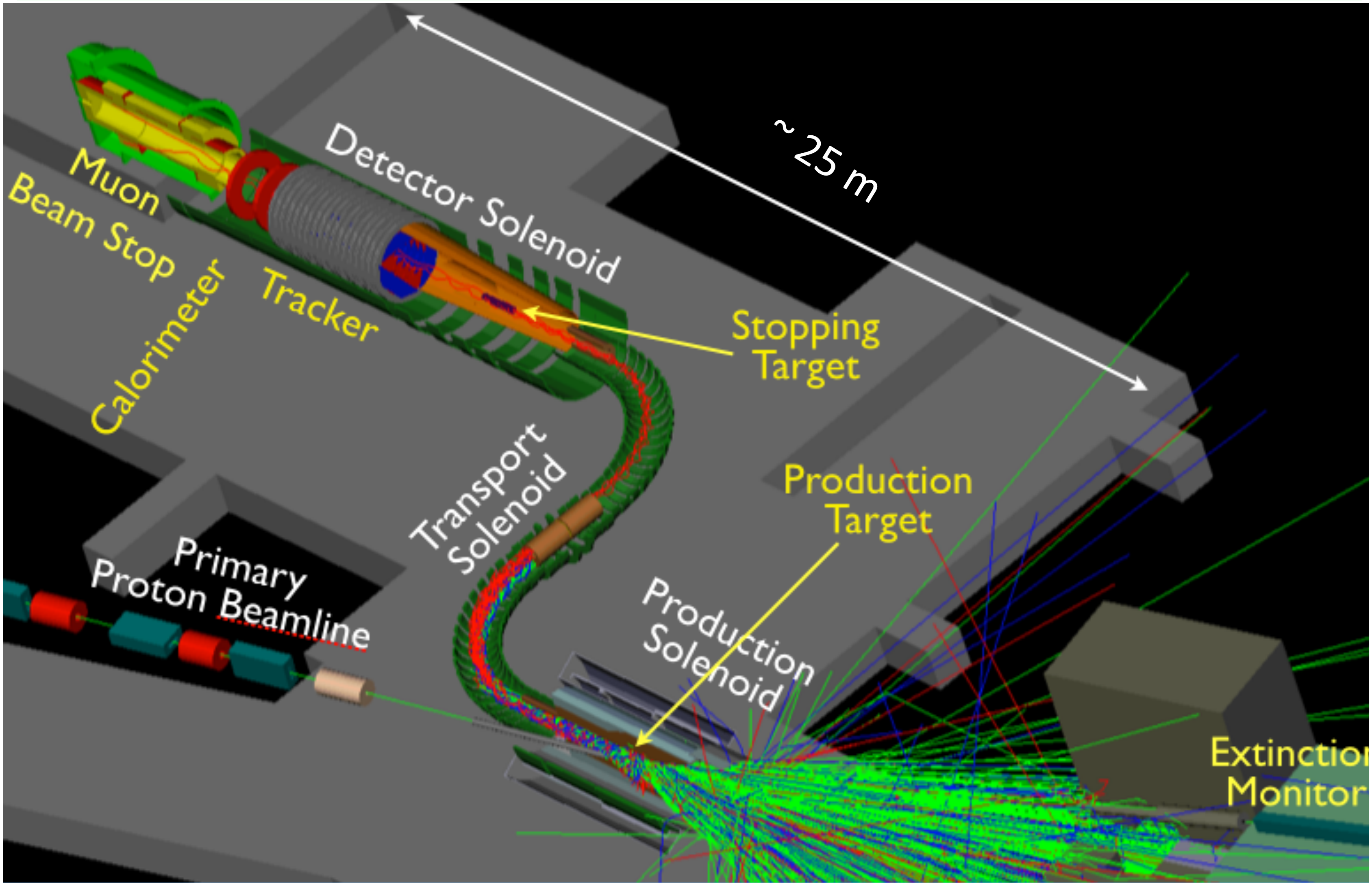


Figure 7.18. Preliminary singles germanium spectrum from the AlCap experiment at PSI. When muons stop in aluminum, they capture on the nucleus 60% of the time. A fraction of the captures produce ^{27}Mg in the ground state, which has a half-life of 9.5 minutes. In the decay, an 844 keV gamma is produced 72% of the time.

- Need a high precise gamma detector (HpGe)
- Energy of gamma ray is unique to the detector
- Detecting the delayed gamma rays eliminate problems related to beam flash

Overall view of Mu2e



Mu2e Experiment Status

- CD2 for detectors (baseline/TDR) obtained on the 5th of March 2015
- CD3b for Civil Construction and start for TS Bid obtained on same date.

→ Procurement of Superconducting cables in progress
→ BID for DS/PS assigned to General Atomics (USA)
→ BID for TS completed. Assigned to ASG superconducting (ITALY)
→ Civil Construction started: **Ground Breaking Cerimony Apr. 18 2015**

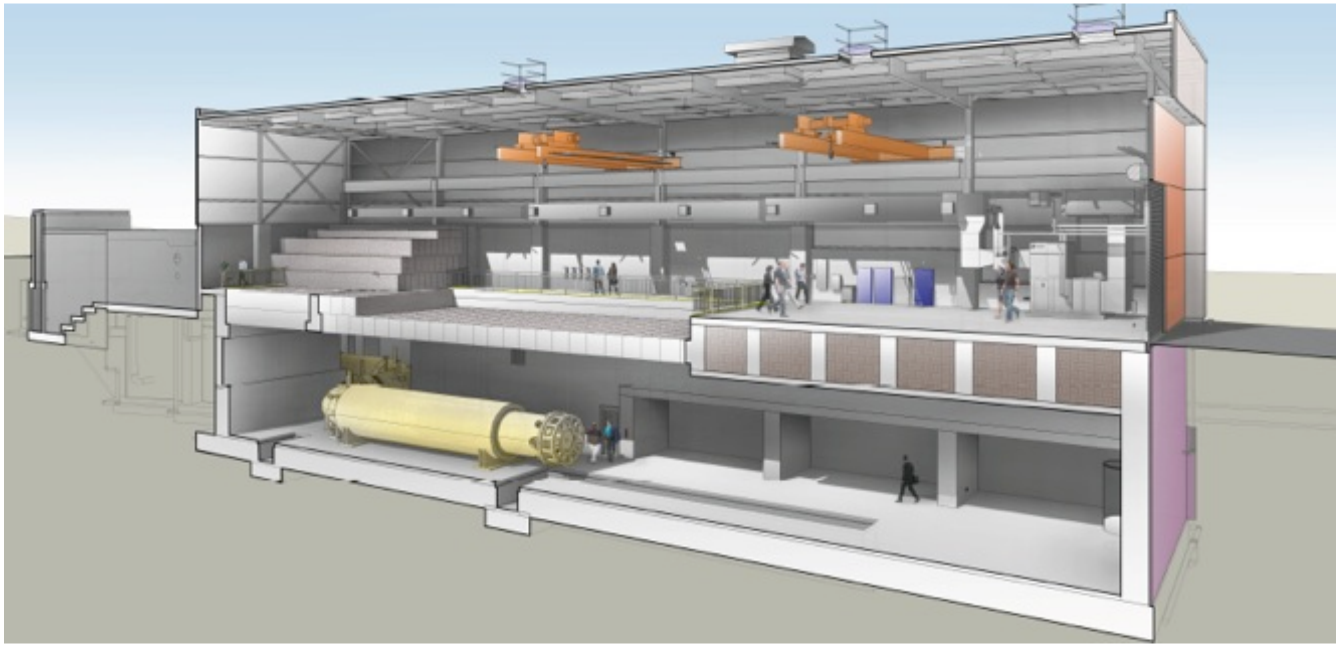
- CD3 for detectors planned for summer 2016

- **INFN contribution**
  → TS prototype
  → Calorimeter system
  → Analysis

CIVIL construction: from design to reality

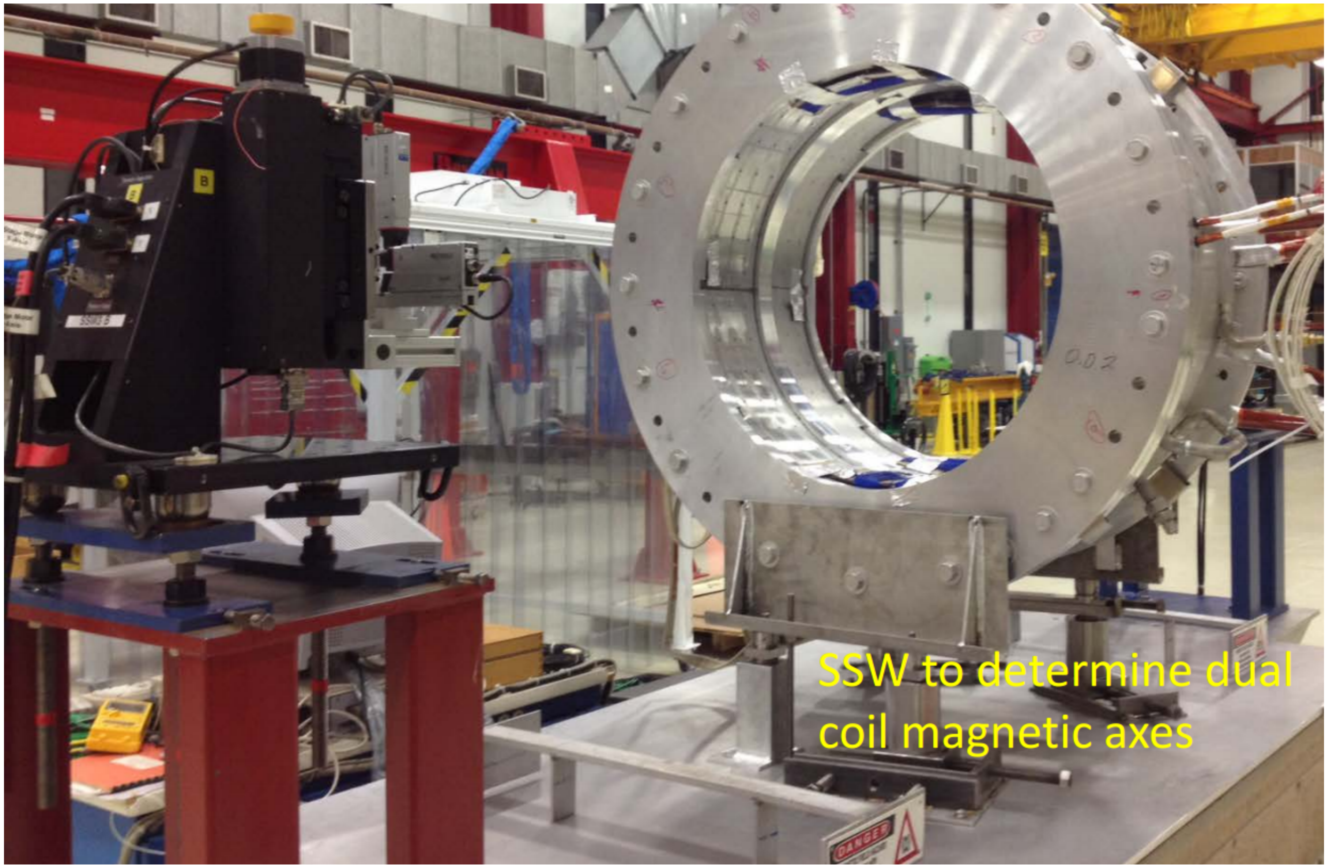
- Six months after Ground Breaking a large part of the concrete has been finished.

- Expect to have a Building ready for the spring!



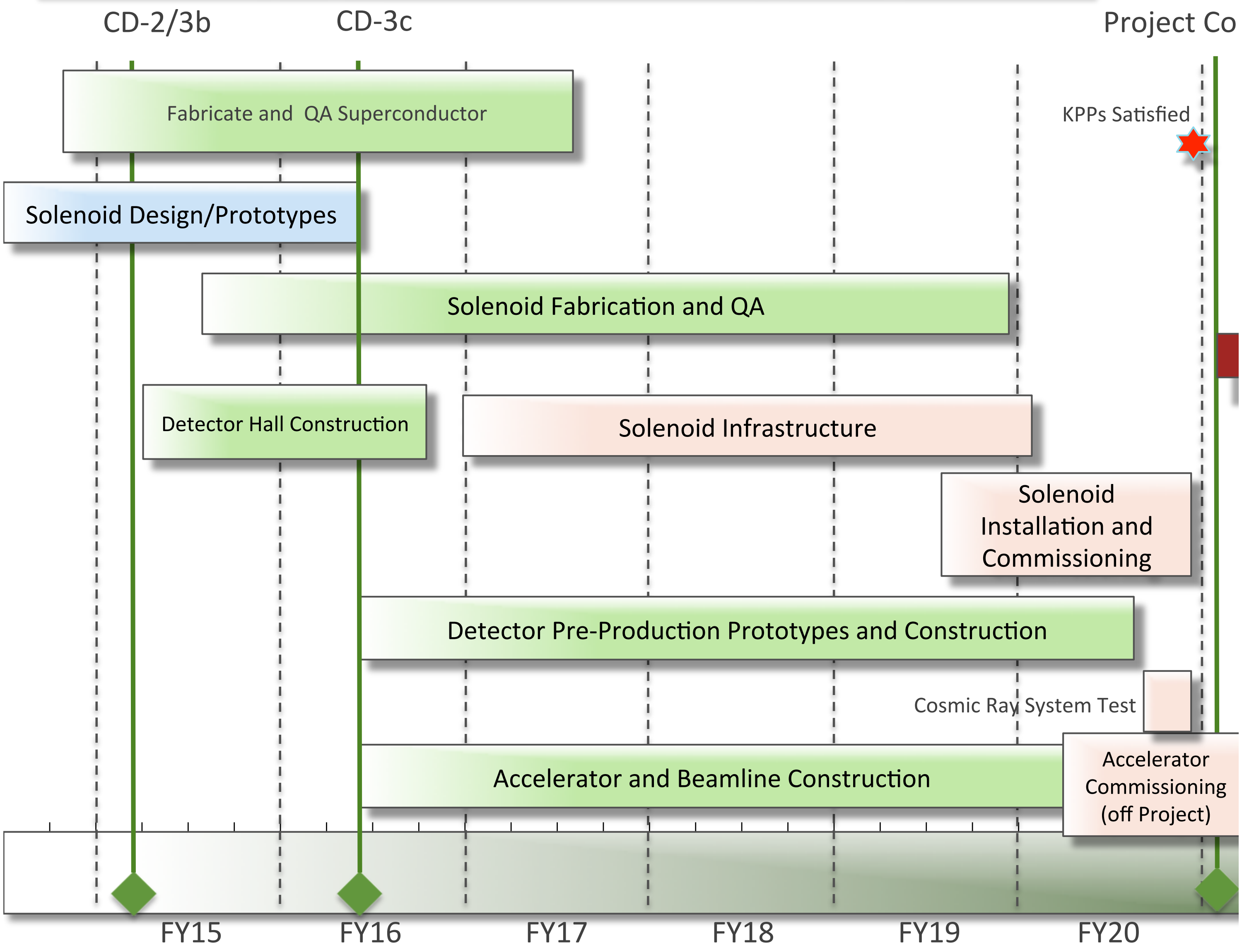

October 2015

TS prototype


SSW to determine dual coil magnetic axes

- ☐ **The Super Conducting magnets are the heart of MU2E Apparatus**
- ☐ TS prototype manufactured by ASG Superconductors, Genova
- ☐ **TS proto @ FNAL tested successfully**
- ☐ **TS BID done → Assigned to ASG Genova**

Mu2e schedule



(WhatNext?) Mu2e … Mu2e-II

Project-X re-imagined to match Budget constraints:

1) PIP-2 plans:

→ 1 MW at LNBF at start (2025)

→ 2 MW at regime at LNBF

→ **x 10 intensity @ Mu2e**

Projectx-docdb.fnal.gov/cgi-bin/
ShowDocument?docid=1232
CLVF-snowmass →Arxiv.1311.5278
Mu2e-2 → Arxiv.1307.1168v2.pdf

2) **Depending on the beam Structure available:**

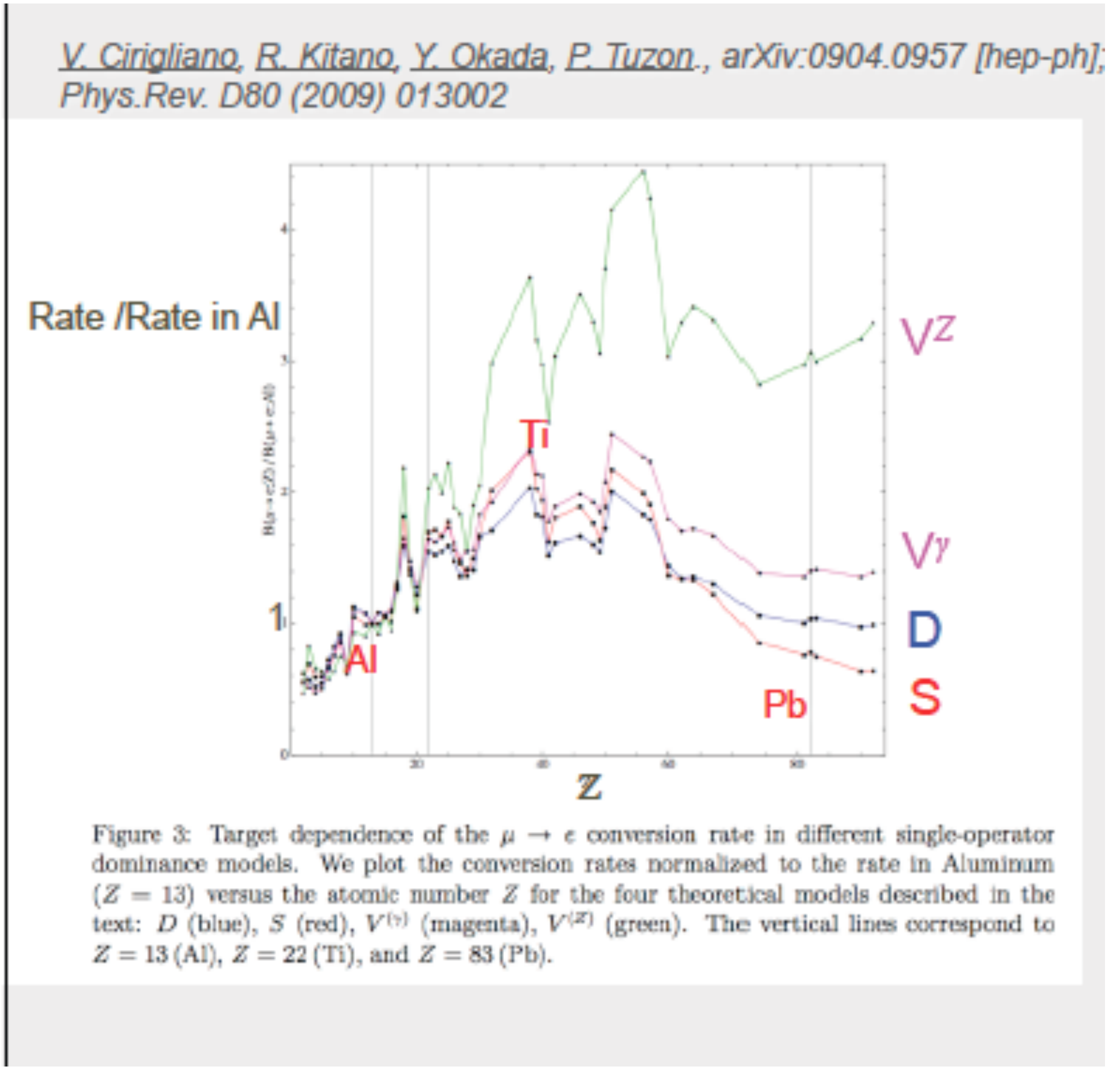
study Z dependence

if signal is observed

3) If no signal is observed

Use x 10 events in Mu2e-2

Minor modifications of the detector → **BR < 6 x 10^{-18}**



V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon., arXiv:0904.0957 [hep-ph];
Phys.Rev. D80 (2009) 013002

Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

ADDITIONAL MATERIAL

COMET vs Mu2e

- Similar capabilities as physics reach

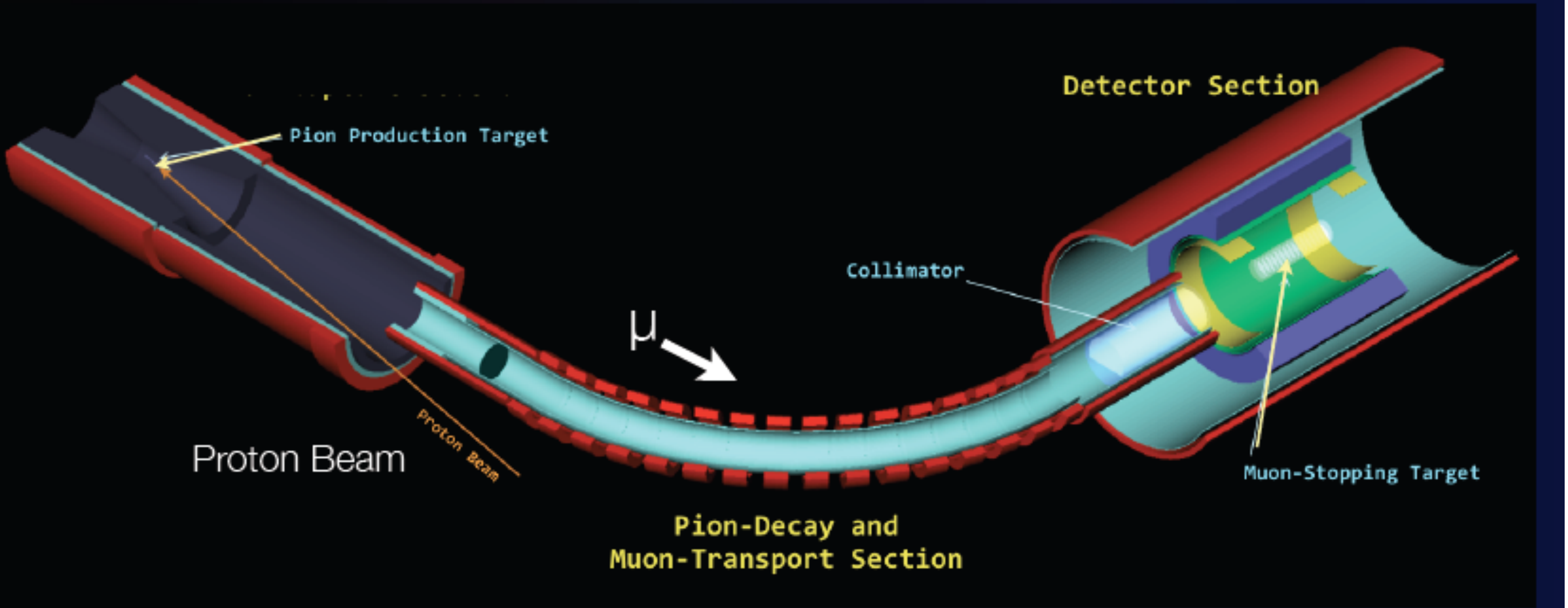
- COMET designed to operate at 56 kW, Mu2e 8 kW
  → COMET will use all JPARC beam
  → Mu2e runs simultaneously with neutrino beam

- Final bend after COMET stopping target efficiently transmits conversion e- and provides rate suppression in detector.

- It does not transmit positrons (no $\mu^- N \rightarrow e^+ N$)
- COMET solenoids ~ 10 m longer than Mu2e
- Higher beam -> higher cost (solenoid shieldling, neutron shielding)
- Longer solenoids carry “cost” in operation

Phase-1 could be useful if successful to study background rate
→ Path to Phase-2 is still difficult.

COMET Phase-I Experimental Layout



COMET muon beam-line :

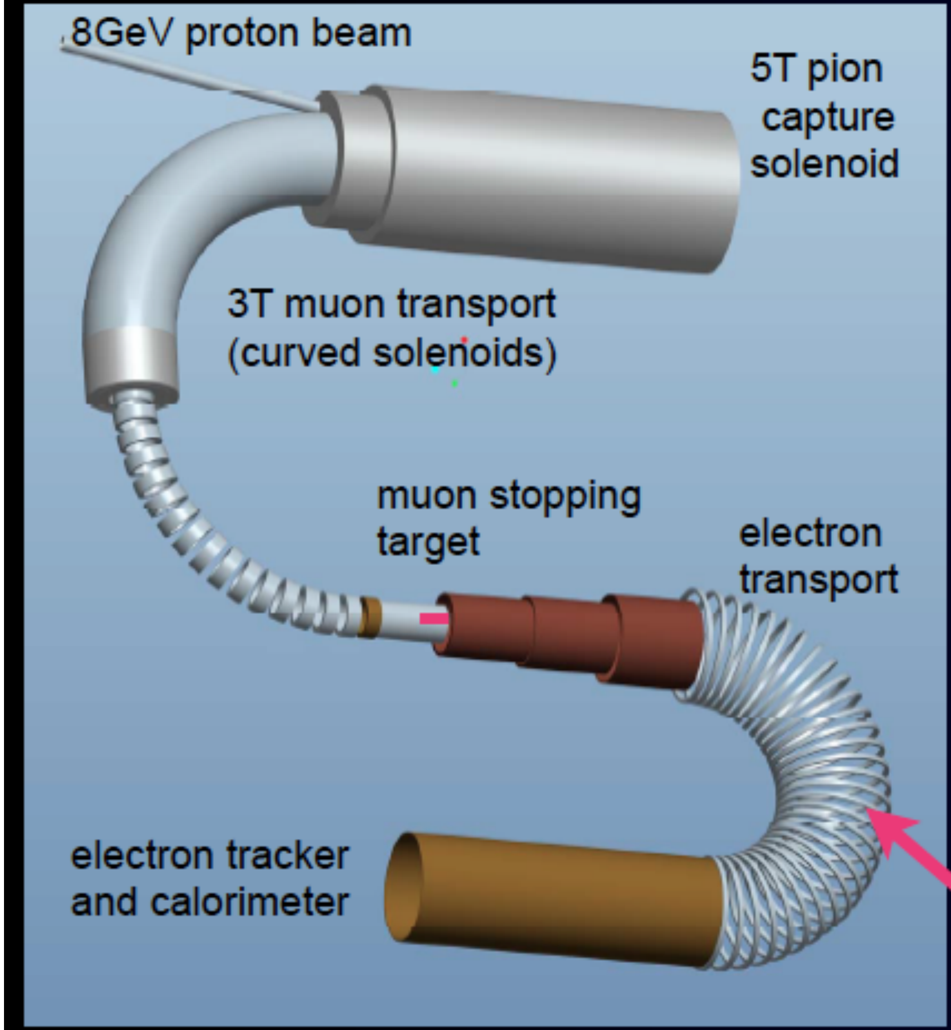
(1~3)x10^9 muon/sec with 3kW beam produced. The world highest intensity.

COMET Phase-I detector :

Cylindrical drift chamber (CDC) for μ-e conversion is used. Straw chamber and ECAL are for beam studies.

Q:physics case coupled with the explicit scope of the experiment

What is COMET (E21) at J-PARC



Experimental Goal of COMET

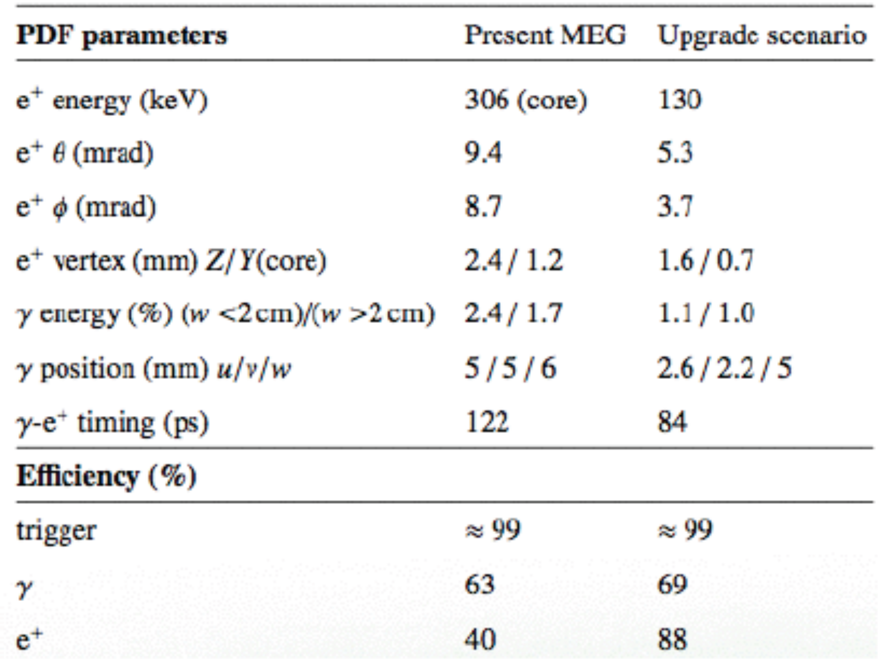
$$B(\mu^- + Al \to e^- + Al) = 2.6 \times 10^{-17}$$

$$B(\mu^- + Al \to e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

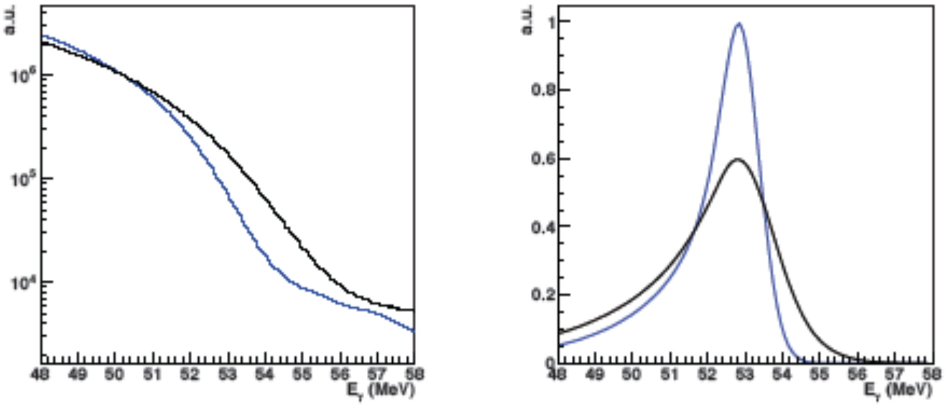
- 10^{11} muon stops/sec for 56 kW proton beam power.
- $2\text{x}10^7$ running time (~1 year)
- C-shape muon beam line
- C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Electron transport with curved solenoid would make momentum and charge selection.

MEG^{UP} sensitivity



PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

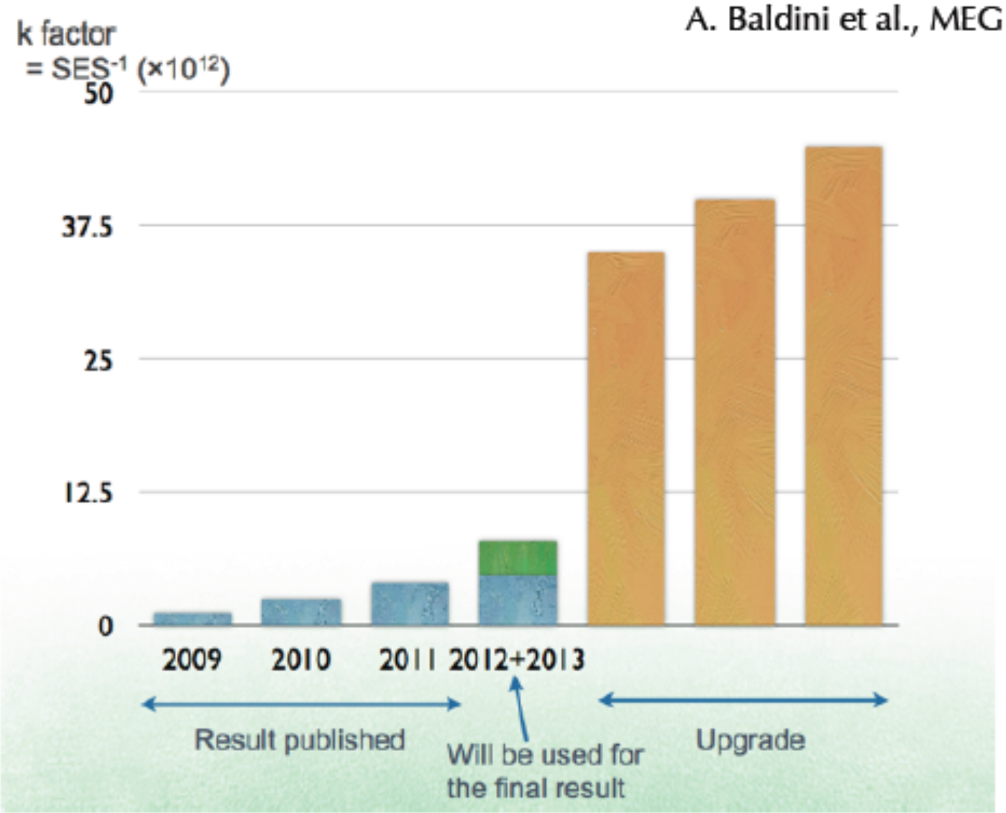


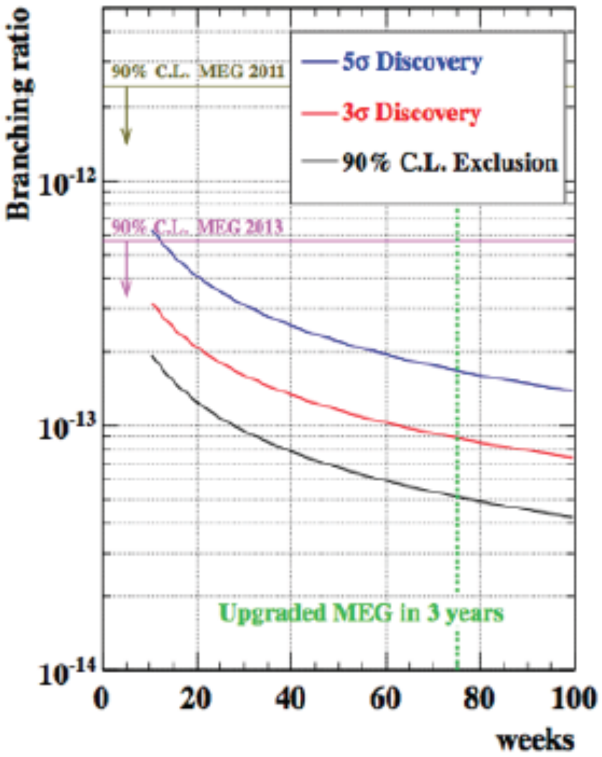
$$5.7 \times 10^{-13}$$

MEG^{UP} sensitivity

- Ultimate sensitivity at the few x 10^{-14} level
- Engineering run 2015
- Data taking 2016-2018

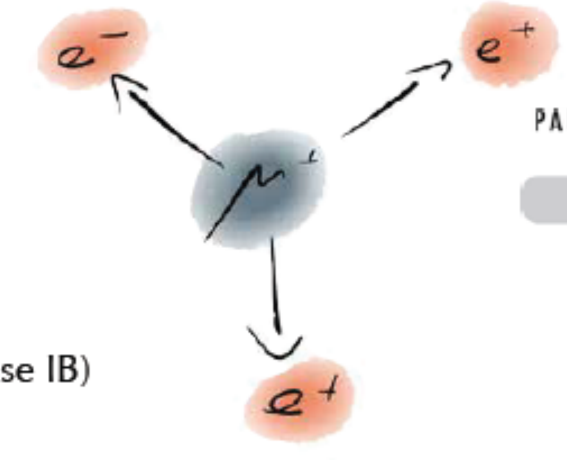
A. Baldini et al., MEG Upgrade Proposal, arXiv:1301.7225 [physics.ins-det] |





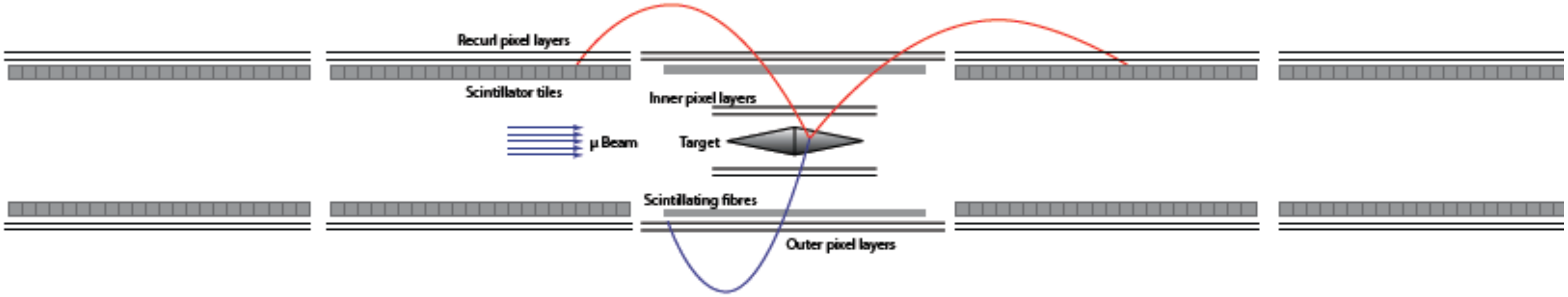
Mu3e at PSI

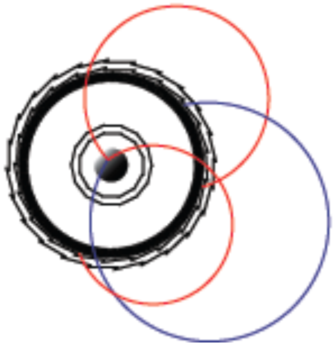
- Search for μ→e e e
  - 10^{-15} sensitivity in phase IA / IB
  - 10^{-16} sensitivity in phase II
- Project approved in January 2013
  - Double cone target
  - HV-MAPS ultra thin silicon detectors
  - Scintillating fibers timing counter (from phase IB)



PAUL SCHERRER INSTITUT

PSI





vw.psi.ch/mu3e

MEG vs Mu3e

- Mu3e decays test also K values larger than MEG but with different (reduced) sensitivity al large k with respect to Mu2e

- Phase 1 Mu3e @ PSI aims to 10^{-15} (approved)

- Next phase aims to 10^{-16} → Not yet approved